CALIFORNIA DIVISION OF MINES AND GEOLOGY

Fault Evaluation Report FER-104

Drew Smith

March 31, 1981

CONTENTS

ILLUSTRATIONS

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I. NAME OF FAULT GROUP

This report includes the evaluation of the Verona fault and portions of the Williams, Las Positas, and Pleasanton faults.

II. LOCATION OF FAULTS

These faults occur in the northern third of the La Costa Valley quadrangle and the southern third of the Livermore quadrangle (Figure 1). The area lies just southeast of the City of Pleasanton, Alameda County, California. Geologically, the area lies just east of the Calaveras fault, and is immediately to the southwest of the Livermore Valley.

III. REASON FOR EVALUATION

The Verona fault is being examined as part of CDMG's 10-year program for identifying and zoning active faults within the State of California (Hart, 1980). The Verona fault, within the La Costa Valley quadrangle, was zoned in 1974 as part of the initial effort of the Alquist-Priolo program to zone the major active faults of the State. It was zoned on the basis of mapping by Hall (1958), and, at that time, no field mapping or aerial photographic interpretations were carried out by the CDMG staff to evaluate Hall's location for the fault or the evidence for recency of activity.

The rationale for zoning Hall's Verona fault was that the fault was considered to be a probable Quaternary fault and it was CDMG policy in 1974 to zone all Quaternary faults that occured within the same quadrangles that the major faults of the state occurred in. The major fault, in this case, is the nearby Calaveras fault. Specifically, the Verona fault was zoned for convenience rather than because it was considered to be a significant potentially active fault (Hart, 1980). The current criteria for zoning a fault, as will be applied by CDMG in this investigation, is that it must be sufficiently active and well defined. A fault is deemed sufficiently active if there is evidence of Holocene (past 11,000 years) surface displacement along one or more of its segments or branches.

Since 1977, the Verona fault, or what is thought by Herd (1977, 1978) and by Herd and Brabb(1980) to be the Verona fault, has undergone extensive investigation to determine what potential hazard it may pose to the nearby General Electric test reactor (GETR). The results of those investigations, although still controversial, have cast considerable doubt on the validity of the fault shown on the 1974 Special Studies Zones Maps, La Costa Valley and Dublin quadrangles (California Division of Mines and Geology, 1974), and, therefore, to the appropriateness of the special studies zone that was established along that fault. Therefore, the Verona fault is being re-examined for the purpose of modifying the existing special studies zone, if necessary.

IV. LIST OF REFERENCES

Bolt, B.A., and Hansen, R.A., 1980, Seismicity of the Livermore Valley in relation to the General Electric Vallecitos plant. Unpublished report ??

California Division of Mines and Geology, 1974, Special study zones official maps, La Costa Valley quadrangle and Dublin quadrangle.

Dibblee, T.W., Jr., 1980, Preliminary geologic map of the La Costa Valley quadrangle, Alameda County, California: U.S. Geological Survey Open-File Report 80-533A. Verona fault after Herd (1977).

Dibblee, T.W., Jr., 1980, Preliminary geologic map of the Livermore quadrangle, Alameda County, California: U.S. Geological Survey Open-File Report 80-533B. Verona fault after Herd (1977).

Earth Sciences Associates, 1978, Geologic investigation, General Electric test reactor site, Vallecitos, California: consulting report for General Electric Company by Earth Sciences Associates, Palo Alto, California, with Addendum 1, April 1978.

Earth Sciences Associates, 1979, Geologic investigation, phase II, General Electric test reactor site, Vallecitos, California: consulting report for General Electric Company by Earth Sciences Associates, Palo Alto, California.

Ellsworth, W.L., and Marks, S.M., 1980, Seismicity of the Livermore Valley, California, region 1969-1979: U.S. Geological Survey Open file Report 80-515, 42 p.

Hall, C.A., Jr., 1958, Geology and paleontology of the Pleasanton area, Alameda and Contra Costa Counties, California: University of California Publications in Geological Sciences, v. 34, n. 1, 90 p.

Hart, E.W., 1980, Fault-rupture hazards zones in California: California Division of Mines and Geology Special Publication 42, 25 p.

Herd, D.G., 1977, Geologic map of the Las Positas, Greenville, and Verona faults, eastern Alameda County, California: U.S. Geological Survey Open-file Report 77-689, 25 p.

Herd, D.G., 1978, Map of Quaternary faulting along the northern Calaveras fault zone: Las Trampas Ridge, Diablo, Dublin, Niles, and La Costa [Valley] 7 1/2' quadrangles, California: U.S. Geological Survey Open-File Report 78-307.

Herd, D.G., and Brabb, E.E., 1979, Evidence for tectonic movement on the Las Positas fault, Alameda County, California: U.S. Geological Survey Open-File Report 79-1658, 7 p.

Herd, D.G., and Brabb, E.E., 1980, Faults at the General Electric test reactor site, Vallecitos Nuclear Center, Pleasanton, California: U.S. Geological Survey Administrative Report, 77 p.

Nuclear Regulatory Commission, 1979, Geosciences Branch safety evaluation report input, GE test reactor site/Vallecitos Nuclear Center. Dated September 10, 1979.

Rice, S., Stephens, E., and Real, C., 1979, Geologic evaluation of the General Electric test reactor site, Vallecitos, Alameda County, California: California Division of Mines and Geology Special Publication 56, 19 p.

Rogers, T.H., 1966, San Jose Sheet: California Division of Mines and Geology, Geologic Map of California, Olaf P. Jenkins Edition.

Savage, J.C., Prescott, W.H., Lisowski, M., and King, N.E., 1981, Strain on the San Andreas fault near Palmdale, California: rapid, aseismic change: Science, v. 211, p. 56-58.

AERIAL PHOTOGRAPHY USED BY CDMG FOR THIS INVESTIGATION:

DESIGNATION:	BUT USDA (1939)
TYPE:	vertical, stereo, black and white
SCALE:	1:20,000
DATE FLOWN:	July 1939 and June 1940
COVERAGE:	Alameda County
AVAILABILITY:	The National Archives, record group #145
FRAMES USED:	281-4 to 281-11, 341-83 to 341-85, and 341-49 to 341-51

DESIGNATION:	BUT USDA (1950)
TYPE:	vertical, stereo, black and white
SCALE:	1:20,000
DATE FLOWN:	March 12, 1950
COVERAGE:	Alameda County
AVAILABILITY:	USDA Agricultural Stabilization and Conservation Service Aerial Photography Field Office P.O. Box 30010 Salt Lake City, Utah 84130
FRAMES USED:	3G-77 to 3G-83, 3G-106 to 3G-113, 4G-11 to 4G-18, and 4G-46 to 4G-52

DESIGNATION:	USGS Low Sun (1973)
TYPE:	vertical, stereo, natural color
SCALE:	1:20,000
DATE FLOWN:	September 21, 1973
COVERAGE:	Alameda and Contra Costa Counties
AVAILABILITY:	RAPID COLOR Glendale, California
FRAMES USED:	1-4 to 1-9, 1-45 to 1-49, and 1-82 to 1-88

V. SUMMARY OF AVAILABLE DATA

A. Hall (1958):

Hall mapped the Verona and Williams faults, and a number of other short faults to the west and south of the Vallecitos Valley area. These are shown, using a solid-line symbol, on Figure 2 of this report. Of these, he discusses only the Verona fault in his text. He portrays the Verona fault, in cross section, as a nearly vertical fault, and says that the northeast side of the fault has been upthrown since the Livermore Gravels were deposited, but that the underlying Miocene rocks were upthrown on the southwest side of the fault during some earlier episode of fault movement.

Hall makes no statements about the recency of movement along the Verona fault, although, on p. 42, he says, "Springs and small ponds occur along the trace of the fault." He does not indicate where these ponds are, or if they are of the type that could have been generated by fault movement, such as sag ponds.

B. HERD (1977):

Herd mapped the Verona fault, along with the Las Positas and Greenville faults that lie to the east. Those parts of his mapped faults that lie within the area under consideration in this FER are shown, using a long-dash symbol, on Figure 2 of this report. Herd mapped the Verona fault at a location different from that shown by Hall (1958). In the vicinity of GETR, Herd maps the fault from 300 meters to 600 meters farther to the south. To the northwest, he plots a course for the fault that differs substantially from that shown by Hall.

Herd locates the Verona fault essentially at the base of the eroded escarpment that extends along the western and southwestern margins of the Vallecitos hills (the unnamed hills that lie to the north of Vallecitos Valley are herein referred to as the "Vallecitos hills"). As a basis for this fault location, Herd argues (p. 14), "The change in elevation in Livermor Gravels in the ridge southwest of Livermore Valley and west of the ridge occurs at the escarpment, not oblique to it." Since he locates the Verona fault at the base of the escarpment, he apparently believes that that is where the change in elevation in the Livermore Gravels occurs. He cites no specific evidence for that interpretation.

Herd says nothing about the attitude of the fault, nor does he mention having seen any exposures of the fault. He says (p. 14-15) that he observes no offset alluvial strata younger than the Livermore Gravels along the Verona fault, but that repeated movement probably occurred during Pleistocene time.

Herd mapped the Las Positas fault, which is a northeast-southwest trending fault that extends from the northeastern part of Vallecitos Valley to the Greenville fault at the eastern side of Livermore Valley. He locates the Las Positas fault, to the northeast of Arroyo Valle, on the basis of scarps and exposures. To the southwest of Arroyo Valle, he locates the fault at the contact between the Miocene Cierbo Sandstone and the Pliocene Livermore Gravels. In that area, he cites no exposures or geomorphic evidence for the location of the fault.

The exposures of the fault to the northeast of Arroyo Valle show it to be high angle. Herd (p. 12) cites evidence for south-side-up sense of offset along the Las Positas fault, including that part of the fault that lies southwest of Arroyo Valle. He cites evidence for faulting of alluvial units as young as late Pleistocene age, but it is not clear from his text whether he believes Holocene sediments have been offset by the fault.

C. Earth Sciences Associates (1978):

Earth Sciences Associates (ESA) conducted this investigation to determine the geologic setting of the General Electric Test Reactor (GETR) site, and the surrounding area, for the purpose of assessing the safety of GETR with respect to geologic and seismic hazards. This study was particularly concerned with the potential for surface faulting at the GETR site, because of the proximity of the Verona fault as mapped by Herd (1977).

Three trenches and three boreholes were excavated as part of this investigation. Their locations are shown in Figure 3. Trenches T-1 and T-2, excavated at the base of the main hill front, both revealed multiple shears dipping to the northeast (into the hill front) at angles that are typically between 10 and 30 degrees. Strata of the Plio-Pleistocene Livermore Gravels are thrust over late Quaternary alluvial and colluvial strata along these shear zones. The logs for these trenches do not show the shears penetrating the modern soil horizon. The total offset on the principal shears cannot be determined from the trench evidence, but the minimum value would have to be at least 10 meters. The log for trench T-2 shows that slickensides were observed along some of the northeast-dipping shear planes. These slickensides have bearings ranging form N20E to N60E. The logs for trenches T-1 and T-2 do not show the profiles of the original ground surface along the trenches. Therefore there is no documentation of the topographic character of the ground surface at the places that are on the plane of projection of the main shears.

Trench T-3 was excavated in an anamolous east-west trending swale located upslope and north of trench T-1. That trench exposed no significant shears, but it was of insufficient depth (15 feet) to penetrate the base of the colluvial deposits filling the swale. The 3 boreholes were excavated between trenches T-1 and T-3, and encountered the main shears that were observed in trench T-1.

ESA (p. IV-33) attributes the thrust shears observed in the trenches to an ancient large-scale landslide complex along the southwestern side of the Vallecitos hills, and say (p. V-3) that there is no fault along the hill front or in the vicinity of GETR. Their argument for the existance of the ancient landslide complex is based on geomorphic features and disrupted bedding in that area. The principal geomorphic feature is a "head scarp-bench-toe geomorphic form" that they say is clearly visible in very low altitude oblique aerial photos of the area. Such a landform is apparently visible in Photos 6, 7, and 8 of their report. They say that the landslide has been so modified by erosional dissection that it is difficult to recognize it as a landslide on the ground. They suggest that the slide movement occurred between 10,000 and 40,000 years ago.

ESA also presents other evidence relevant to the question of whether a fault, especially a thrust fault, exists in the vicinity of GETR. They cite evidence (p. IV-23, 24) for ongoing north-south extensional stress across the Livermore Valley area, based on a network of geodimeter measurements in the region. They also state (p. IV-26) that Vallecitos Valley and La Costa Valley are of erosional (as opposed to tectonic) origin, and that the relatively linear southwestern front of the Vallecitos hills is also of erosional origin.

Addendum 1 (dated April 1978) to the ESA (1978) report, addresses some questions that were raised informally by the USGS. The most significant of these was the great decrease in thickness of the Livermore Gravels to the southeast of the Vallecitos hills as compared to the strata beneath the hills. The USGS apparently cited this as evidence for the existance of the northeast-trending Las Positas fault in that area. ESA counters that such rapid thinning near the margin of alluvial fan deposits is common, and that, in this case, the area under consideration has those characteristics--the source area for the gravels being the Diablo uplift to the southeast and the depositional area being the Livermore Basin to the north. ESA attributes this condition, and not faulting, as the cause of the abrupt thinning of the Livermore Gravels in that area.

D. Earth Sciences Associates (1979) "Phase II":

ESA states (p. II-1) that the purpose of their "Phase II" study was, "...to determine whether the postulated Verona fault exists, whether air-photo lineaments crossing the site are fault or bedding related, and corroborate previous findings that the low-angle shear planes at the base of the hillfront are landslide features rather than fault features." Trenching was the principal investigative method, and the trenches supplied most of the new information that was gathered during the Phase II study.

Trench A and subsidiary trenches A-1 and A-2 were excavated in the pass area about 12,000 feet east-northeast of GETR and south of Highway 84 (see Figure 2 for location). The purpose, apparently, was to explore for an eastward continuation of the Verona fault that had been postulated by USGS staff personnel. The trenches revealed a fault in Livermore Gravels striking N65-70W and dipping 70-75NE. ESA says (p. III-20), "The main shear zone exhibits well-developed mullion shear structure and striations trending along strike and plunging 2-11 degrees northwest, indicating predominately strike-slip movement." They also note that adjacent bedding in the Livermore Gravels is warped and dragged in a right-lateral sense. They say that the modern soil profile is not affected by the faulting.

Trench E was excavated at the base of the hill front about 15,000 feet northwest of GETR (see Figure 2 for location). The purpose of that trench, apparently, was to investigate a northwest-trending lineament, near the base of the hill front, that constituted part of the evidence upon which Herd (1977) based his location of the Verona fault in that area. The trench revealed several small northwest-trending, southwest-dipping shears, but no evidence for high-angle or thrust faulting as postulated by USGS. The trench revealed some relatively young northwest-trending alluvial channel deposits, and ESA attributes these, along with near-surface ground water conditions, as being the source of the observed photolineaments in that area.

Trench B-1, about 1080 feet long, was a northeast-trending trench that lay about 300 feet northwest of GETR (Figure 3). This trench, apparently, was excavated to allow another subsurface look at the base of the hill front, and to investigate a topographic lineament that trends sub-parallel to the hill front and lies about 800 feet to the southwest of the hill front. This trench revealed thrust shears at the base of the hill front that are similar to those observed in trenches T-1 and T-2. At the location of the topographic lineament, the trench revealed no shears or other indication of the cause of that lineament.

Trench B-2 is more or less a southwestward continuation of trench B-1 (Figure 3). It was excavated to examine another northwest-trending topographic lineament that lies about 400 feet to the southwest of the end of trench B-1. This trench revealed a significant northwest-trending shear that dips 20 to 30 degrees northeast. This shear, like those at the base of the hill front, has also thrust Livermore Gravels over late Quaternary alluvium and colluvium. This shear is not at the location of the observed topographic lineament, but is about 100 feet upslope from it. The surface projection of this shear is associated with no topographic lineaments or other features. ESA (p. III-23) says that the Holocene soil is not offset by this shear. The log for trench B-2 shows a small sub-parallel shear about 40 feet upslope from the main shear. This small shear has slickensides trending N65E.

Numerous short subsidiary trenches to B-2 were excavated to the northwest and southeast to trace the course of the main shear observed in trench B-2. The shear was exposed by these short trenches for about 400 feet to the northwest and for about 800 feet to the southeast, but beyond those points it could not be found.

Trench B-3 is located at the base of the hill front, about 500 feet due east of GETR (Figure 3). The trench revealed a zone of shearing similar to what was observed in trenches T-1 and B-1. The main shear strikes N60-65W (parallel to the hill front) and dips 15 to 20 degrees to the northeast (into the hill front). The log for this trench indicates grooves and striations on the shears. These indicators of slip movement trend from N38E to N55E. ESA says (p. III-25) that the direction of these grooves and striations indicates "minor right-lateral oblique slip." It appears to this writer that this is erroneous; the geometry of these features indicates a minor LEFT-lateral component of offset.

Trench H was a north-south-trending trench excavated about 2500 feet south-southwest of GETR. Its purpose was to investigate another photolineament in the area. The trench revealed one significant shear that strikes N85W and dips 20 to 30 degrees north. This shear, like the other principal shears already discovered, shows Livermore Gravels thrust over late Quaternary alluvium and colluvium. Grooves and striations on this shear trend N30E to N40E. The photolineament lies about 25 feet downslope from the surface projection of the main shear. The ground surface at the site of this trench had been graded at some earlier time, so it could not be determined whether the shear offset the modern soil. Older paleosols were observed to be offset. In this trench, like all of the others, the total offset along the principal shear cannot be determined from the available evidence. It appears, from the trench log, that the minimum offset would have to be 10 meters.

Two other subsidiary trenches were dug in an attempt to follow the shear zone along strike. Trench H-1, about 50 feet to the east of trench H, exposed the shear, but trench H-2, about 250 feet west of trench H, did not.

Trenches D, F, and G were all excavated along the north-northeast-trending ridge spurs in the hill front to the north of GETR. The purpose of these trenches was to seek evidence for the large-scale landsliding that ESA had previously postulated. Specifically, it was hoped that these trenches would reveal evidence for headwall pull-away breaks, and evidence for the mechanical disruption of bedding that a landslide would be expected to cause. Some evidence, in the form of shears, was found to support the landslide hypothesis, but, in general, there was far less evidence than what would have been expected if the landslide exists. It should be noted that these trenches were nominally 5 feet deep--as compared to most of the other trenching which was usually at least 10 feet deep.

ESA concludes (p. I-1), "No evidence was disclosed which conclusively proves whether the shears on the GETR site originated as the result of large-scale mass wasting or of tectonic faulting, although we believe that the landslide hypothesis remains the most reasonable explanation."

Regarding recency of movement along the shears, ESA says (p. I-2), "Measurements of offset soil stratigraphic markers confirm that no offset has occurred on any of the shear surfaces within the last 8,000 to 10,000 years, and that the maximum amount of reverse dip-slip offset within the last 20,000 years is less than one meter."

Regarding the Las Positas fault, ESA says (p. III-13) that the trace mapped by Herd (1977) to the southwest of Arroyo Valle, along the Cierbo Sandstone-Livermore Gravels contact, is in fact an onlap depositional unconformity, and not a fault. In a more general statement (p. III-15), ESA says that the existence of the Las Positas fault is not supported by existing geologic data.

Regarding the northwest projection of the Verona fault--toward Pleasanton--ESA says (p. I-1) that evidence from surface outcrops, trenching, seismic reflection data, and water well data does not support the existance of such a fault.

APPENDIX A to ESA (1979):

Appendix A contains a soil-stratigraphic report by R.J. Shlemon. Shlemon recognizes 4 soil formation-related stratigraphic markers in the trenches. These include, from oldest to youngest, (1) a dark red buried paleosol that is between 70,000 and 125,000 years old, (2) a stoneline that is 17,000 to 20,000 years old, (3) a bleached albic horizon that is 10,000 to 15,000 years old, and (4) a modern soil that is at least 8,000 to 15,000 years old. Regarding the age of the modern soil, the radiocarbon ages for it were in the range of 3,000 to 4,000 years. However, Shlemon estimates the actual minimum age to be between 8,000 and 15,000 years; the difference is a fudge factor to offset the continuing contamination of the soil by young carbon.

Shlemon (p. A-39) says that the shears in trenches B-1 and B-2 displace the first 3 horizons, but not the fourth. In trench E, none of these horizons are cut by the shears that were observed. He notes (p. A-31) that the dark red paleosol is traceable continuously along the entire length of trench E, and is essentially parallel to the present surface. He says, "This 'paleo' and modern topographic parallelism indicates well the relative stability of the GETR area, at least in late Quaternary time."

APPENDICES C and D to ESA (1979):

Appendices C and D are reports of siesmic reflection and seismic refraction surveys that were conducted in an attempt to obtain more information about the existance and location of the Verona fault and other structural features in the area. These methods provided little useful information, and in some areas, such as the hill front north of GETR, it was concluded that the seismic methods were simply not feasible for their intended purpose. Some definitive subsurface information, indicating that no significant faulting existed in an area near trench E, was obtained using refraction methods. But trench E provided much more substantive evidence for the same conclusion.

E. Herd and Brabb (1979):

This report provides additional information about the character of the Las Positas fault. Based on exposures of the Las Positas fault near Arroyo Seco (about 13 kilometers north-east of GETR), they determined that the fault is high angle and is subject to predominantly left-lateral strike-slip movement. Specifically, this determination stems from the observed direction of slickensides and the observed sense of vertical offset of late Pleistocene terrace gravels along one branch of the fault.

Herd and Brabb (p. 5) say that this sense of offset along the Las Positas fault is structurally compatible with northeast-over-southwest thrusting along the Verona fault, and that the upper plate of the Verona fault has been repeatedly displaced westward. They also say (p. 4-5) that part of an A horizon of the modern soil profile is apparently offset by one of the branches of the fault at the Arroyo Seco exposure, which suggests that there has been Holocene offset.

F. Rice and others (1979):

This report is primarily a recap of the GETR-related investigations that have taken place, and a summary of the existing evidence. Rice, however, did examine many of the trenches, and made observations that in some cases differ from those of the other investigators. Rice and others (p. 7) state:

> Some 1200 feet northwest of B-2, and on the strike of the thrust exposed in it, there is a low-angle thrust exposed in several shallow backhoe trenches (fault 2A on Figure 3). This thrust appears to be arcuate to the northeast in trend. It cuts Livermore Gravels, but does not

> displace the stoneline horizon underlying the youngest colluvium and soils. Thus it is not likely to be continuous with the fault 2 in trench B-2.

However, in regard to this same set of shallow backhoe trenches, ESA (1979, p. III-24) only mentions the occurrence of "irregularly striking shears with irregular near-vertical dips."

Table 1, which is a reproduction of Table 1 in Rice and others, provides an excellent tabulation of the principal thrust shears that were found, their attitudes, the lithologic units that they cut, and the magnitude of offset on each of those units.

Rice and others summarize the evidence for the origin of the shears, both that for landsliding and that for thrust faulting. Their evaluation of the evidence is stated (p. 14):

> In sum, available evidence does not conclusively prove or disprove the origin of the faults exposed in the trenches. It is our judgement, however, that the weight of evidence is strongly in favor of a landslide origin for those features.

G. Herd and Brabb (1980):

This report is primarily a review of the interpretations of Herd and Brabb in regard to the tectonic reality of the area in the vicinity of GETR. They present no significant new evidence, but do disagree with ESA in regard to some of the significant trench evidence.

Herd and Brabb (p. i) say that the arguments for landsliding have no basis in fact. They base this conclusion mainly on the failure of trenches D, F, and G to expose structural evidence for large-scale landsliding, and the lack of significant disruption of bedding which would be expected if the landslide exists.

In regard to the existence of the Verona thrust fault, they say (p. iii) that tectonic faulting is required to explain:

a. Recurrent fault movement.

b. Nearly perpendicular discordance between the middle conglomerate unit and upper member of the Livermore Gravels about 2 miles northeast of the GETR.

c. Drastic thinning of the upper member of the Livermore Gravels eastward across California Highway 84.

d. Continuity of thrust faulting outside the area of the postulated ancient landslide.

e. Steepening downward of the dip of the thrust faults with depth.

They do not explain why recurrent landslide movement would not also account for the recurrent movement on the thrust shears. The "nearly perpendicular discordance in in strike" occurs between beds having shallow dips. Thus, the actual dihedral angle between the beds is only in the range of 20 to 30 degrees. They do not explain why this difference should require a fault explanation in a region where such variations in bedding attitude are common.

In regard to the recency of movement along the principal thrust shears, Herd and Brabb conclude that most of them have displaced the modern soil profile, and that during the latest episode of movement the displacements ranged from 1.5 to 5 feet. They believe that the most recent movements occurred since 2,000 to 4,000 years before present. These conclusions are significantly different than those of ESA (1979). As a basis for these conclusions, Herd and Brabb (p. 9-21) say: (1) ESA did not properly log the trenches, (2) that estimates of the ages of soil development, especially the modern profile, by ESA and Shlemon are wrong, and (3) that the estimated corrections that ESA and Shlemons applied to the C-14 ages are too radical.

In general, the tenor of Herd and Brabb's arguments is that ESA and Shlemon have viewed the evidence in such a manner as to obtain the oldest possible interpretations of the recency of movement. On the other hand, it appears that Herd and Brabb are taking the youngest possible interpretation. The writer cannot at this time ascertain the truth of this issue based on the available information. For some reason no one seems to address the fact that there is no specific geomorphic expression of the thrust shears at the loci of their surface projections.

H. NRC (1979):

This document sets out the position of the NRC Geosciences Branch staff. They accept the Verona thrust fault interpretation for the origin of the thrust shears (p. 10). They accept the interpretation that the thrust shears have displaced Holocene soils (p. 8). They also conclude (p. 10) that a landslide hazard exists at the site of GETR.

I. Ellsworth and Marks (1980):

This report indicates that the seismicity in the vicinity of the Verona fault supports the thrust fault interpretation of Herd and Brabb (1980). Ellsworth and Marks (p. 11) say, "Within the region northeast of the Hayward and Calaveras faults, focal mechanism solutions show a continuous progression from strike-slip to thrust faulting." They cite focal mechanism solutions for several seismic events which they believe support the northeast-dipping thrust fault geometry as proposed by Herd and Brabb (1980).

J. Bolt and Hansen (1980):

This report concludes that the data used by Ellsworth and Marks (1980) is not of sufficiently good quality for useful focal mechanism solutions, and that, therefore, the conclusions of Ellsworth and Marks regarding the existence, geometry, and sense of movement along the Verona fault are unjustified.

VI. INTERPRETATION OF AERIAL PHOTOS AND FIELD OBSERVATIONS

A. The Existance of the Verona Fault:

The geomorphic character of the Vallecitos hills is sufficient to indicate that the hills have been tectonically uplifted relative to the valleys to the south and west. The hills rise at least 200 meters above those valleys, and the boundary--the edge of the hills--is abrupt and relatively linear. The valleys cannot have been created by erosion; they host no drainage systems having sufficient erosional capacity. ESA (1978) argues that Vallecitos and La Costa Valleys are of erosional origin, with the erosion having been accomplished by drainage patterns different than those that exist today. But the valleys are erosionally much more mature than the Vallecitos hills, which is something that the ESA interpretation does not account for. Furthermore, if the valleys had been created by erosion, it would in no way account for the present steep linear front of the hills.

Tectonic uplift of the Vallecitos Hills has to have been caused either by faulting or folding, or a combination of both. Geologic mapping of the Livermore Gravels, which underlie the hills, includes a sufficient density of bedding attitudes to show that folding is probably not the cause of uplift of the hills, and certainly not the cause of the abrupt southern and western margins of the hills. Therefore, one or more faults must occur at the southern and western margins of the hills, and the uplift of the hills is the result of the vertical component of movement along those faults. Therefore, the Verona fault, and perhaps other faults at the margins of the hills, must exist.

B. The Existence of an Ancient Landslide Complex:

The evidence presented below indicates the existance of a large landslide complex along the southwestern side of the Vallecitos hills. The evidence indicates that the origin of the landslide is probably associated with the faulting at the margin of the hills, and that the landslide developed slowly through a long sequence of limited movements.

Figure 3 shows the approximate boundaries of the eroded landslide mass and the now-eroded headwall area. This boundary, in the area downslope from the base of the main hill front, marks the place where the geomorphic continuity of the surrounding terrane is terminated--as observed on aerial photography. As such, it could represent the geomorphic disruption caused either by landsliding or thrust faulting, whichever mechanism is responsible.

The strongest evidence for landsliding lies in the geomorphology of the drainages and ridge spurs that trend northeastward and southwestward from the main drainage divide (figure 3) that extends along the southwestern part of the Vallecitos hills. The drainages that flow to the northeast have all been beheaded. That is, they all once extended from 150 to 500 meters farther to the southwest, and the main drainage divide originally lay that much farther to the southwest than where it presently is.

The evidence for this truncation lies in the geometry of the longitudinal profiles of the drainages and, in part, in the relationship of the drainage profiles to the profiles of the adjacent ridge spurs. A common characteristic of drainages of this scale, in terrane with this magnitude of relief, is that their longitudinal profiles become increasingly concave upward toward the upper end of the drainage. This is to be expected; watershed area decreases toward the head of a drainage, therefore runoff decreases, and therefore erosional down-cutting capacity decreases.

Figure 6 (6a, 6b, and 6c) shows 9 drainage and 7 ridge spur profiles, and Figure 5 shows the locations of those profiles. Drainage profiles D1 through D4 (figure 6a) represent control for this test. These drainages occur in the same lithological setting as the landslide terrane, but have obviously not been involved in any processes that would have removed any significant part of the upper end of the drainages. The profiles clearly show the abrupt increase in upward concavity (i.e. decrease in radius of curvature) near the heads of the drainages. Notice also that the heads of the drainages extend upward to almost the elevation of the adjacent ridge spurs. Compare these profiles to profiles D5 through D9 (figures 6b and 6c). Note that the northeast-flowing drainages exhibit almost no increase in gradient near their heads, except for a slight lip right at the heads of two of the drainages. Note also that the heads of the drainages are much lower in elevation than the adjacent ridge spurs. Both of these features indicate that the drainages at one time began farther to the southwest than where the present main drainage divide is located. The slight lip at the heads of some of these drainages probably represents the early stages of the re-establishment of a normal stream profile.

In Figure 7, the profiles from the control drainages (D1 through D4) have been superimposed onto the profiles of the drainages that flow northeastward from the divide (D5 through D9). A "best fit" match of the profile gradients was employed to show approximately how much of the original heads of drainages D5 through D9 has been truncated. Also shown is the probable position of the most northeasterly headwall slide plane (assuming that there may have been more than one slide plane).

The evidence, cited above, for the truncation of the northeastward-flowing drainages does not bear on the question of how the truncation occurred. If the landslide did not exist, one would have to assume that the heads of those drainages were eroded by active headward advance of the southwestward-flowing drainages. The southwestward-flowing drainages have a local drainage base (the margin of the hills) that is at an elevation of about 600 feet. The same is true for the northeastward-flowing drainages, but the distance from the heads of those drainages to the local base is about twice as far (typically about 2 km) as it is for the southwestward-flowing drainages (typically about 1 km). Therefore, the southwestward-flowing drainages have twice the average gradient and significantly more erosional capacity. As such, the main drainage divide should be migrating toward the northeast, and that is undoubtedly what is happening. However, there is other evidence that landsliding must have occurred, that a landslide headwall must have formed, and that headward erosional advance of the southwestward-flowing drainages can only have accounted for part of the truncation of the heads of the northeastward-flowing drainages.

Figure 8 shows the locations of the 5 topographic cross sections that are shown in Figures 9 and 10. Cross sections AA', BB', and CC' (figure 9) all look northeast, and are essentially perpendicular to the dominant northeastward- or southwestward-flowing drainages and to the intervening ridge spurs. Note, on sections AA' and CC', that the pitch of the spacing of the ridges is on the order of 300 to 500 meters, and that the typical relief is about 30 meters. By comparison, section BB' through the area just southwest of the main drainage divide shows an average pitch of only about 150 meters, and the relief between adjacent drainages and ridges is only about 15 meters. The prominent ridges, which characterize the geomorphic development of this terrane, are noticeably absent in the area just southwest of the main drainage divide.

One might try to explain this anomaly as being characteristic of the rapid erosion that occurs along a hill front that is being actively uplifted along a bounding fault. That explanation, however, begs the question as to why the anomalous topogrophy is developing only at a distance of 1/2 to 1 kilometer from the hill front, and not closer to the margin of the hills--as at the location of section AA'. Also, consider the ridge spur profiles R4, R6, and R7 shown in Figures 6b and 6c. In each case, the ridge spur has a subordinate peak near its southwestern end, typically about 300 m from the margin of the hills. It is difficult to explain how erosion could have "bypassed" the ridge spurs at the front of the hills, and then so thoroughly removed them farther up stream. There is no apparent difference in the local lithological resistance to erosion that would be sufficient to account for this anomalous erosional configuration.

These topographic characteristics are typical of those created by landsliding. The peaks near the southwestern ends of the ridge spurs are the displaced former peaks of the main drainage divide. The main divide gradually slid down to its present position. With sufficiently slow landslide development, ponding at the base of the headwall would have been sufficient to allow overflow across the sliding divide, and, therefore, to allow the establishment of through-flowing southwestward drainages as exists there today. The landslide process also accounts for the removal of major ridge spurs in the area immediately southwest of the present main divide.

The narrow pitch and low relief in the topography just southwest of the main drainage divide (section BB', figure 9) are characteristic of the drainage patterns that would be expected to form on a newly-created undissected slope. The scarp development presents a new, relatively planar, steep surface which erosional processes begin to modify. At first the headwall surface is dissected by many shallow, closely spaced, small drainages. Through time these gradually coalesce, leading to fewer drainages and greater relief. Given sufficient time, erosion will mature the topography of the headwall area to the extent that it is geomorphically indistinguishable from the surrounding terrane. The topography of this headwall area, as shown in section BB', is about half way in its erosional maturity to coming into equilibrium with the surrounding terrane.

Another characteristic of the maturation of an eroding terrane is the development of soil, and the resulting effect of the layer of soil on the erosional process. The most noticeable effect is the "softening" or rounding-off of the angularity of the ridge and valley topography. If a surface having no soil development is exposed to erosion, as in the case of a landslide headwall scarp, the newly developed drainages and ridge spurs tend to have a V-shaped or sawtooth-shaped cross sectional appearance. As soil develops, usually over a period of tens of thousands of years, those valleys and ridge spurs gradually develop cross sectional appearances that are more sine wave in character than sawtooth. Sections DD′ and EE′ (figure 10) show the cross sectional character of 2 areas, each having a sequence of small drainages developed on a moderately steep slope. These cross sections were prepared from a large scale topographic map having a contour interval of 10 feet (Earth Sciences Associates, 1979, figure 2). Section DD′, taken near the margin of the hill front, shows the sine wave cross section which is typical for drainages that develop on the Livermore Gravels in this region. Section EE′, taken just southwest of the main drainage divide, shows the more sawtooth-type cross section that is typical mainly only in the area just southwest of that divide. Examination of aerial photography shows that this sawtooth topography occurs in, and is essentially confined to, the same area which, based on other geomorphic evidence, appears to be the site of the headwall of the landslide.

Figure 11 shows the areal distribution of drainages in the area under consideration. The triangles show the location of the main drainage divide, and the dashed line shows the approximate boundary of the landslide mass. The area between the divide and the landslide mass is the eroded headwall area. Note that all drainages in the headwall area consistently flow to the southwest, with none of the branching or perpendicular tributaries that characterize the rest of the region. This is one more line of evidence indicating that a landslide did occur there, and that as the landslide slid, it generated an essentially continuous southwest-sloping headwall for a distance of about 3 kilometers across the southwestern side of the hills.

Figure 4 shows a postulated sequence of events that led to the development of the landslide and its geomorphic appearence as we currently see it. The series of sketches in Figure 4 are diagrammatic and not to scale. They depict the development of landsliding in the hill front area to the north of GETR. Figure 4 shows the initiation of fault offset of an erosionally-planed surface that is underlain by Livermore Gravels that dip monoclinally to the northeast. The Verona fault may have initiated as a new fault at that time, or, more likely, it was the reactivation of a pre-existing fault at depth beneath that location. The vertical component of movement along the fault eventually created a steep hill front that overly stressed the mechanical competence of the underlying clay-rich, poorly consolidated, Livermore Gravels.

At some point in time, perhaps associated with a relatively wet period during one of the late Pleistocene glacial stages, failure began (figure 4d). The toe of the slide, to the southwest of the fault, was probably thrust outward along a clay-rich bedding plane. The fact that the drainages flowing southwestward across the slide mass have maintained their watercourses suggests that the sliding occurred as a multitude of small increments, perhaps only in wet years during periods of unusually wet climate.

Figures 4e and 4f show that ongoing faulting, and the resulting offset of the slide plane, may explain the observed multiplicity of thrust shears in the vicinity of GETR. Figures 4g and 4h show that fault offset may have penetrated the slide mass from time to time, leaving behind a set of abandoned fault planes that would be older to the southwest and younger to the northeast. This phenomena, the evidence for which is discussed below, appears to be reflected in the present topography of the landslide surface in the form of drainage control along the abandoned fault planes.

C. Location of the Verona Fault:

Figure 12 shows the probable location of the Verona fault. This location is based on an anomalous alignment of drainages across the landslide that is very apparent on some of the aerial photography, especially on photo 1-46 of the 1973 color photography (see section IV for a listing and description of the aerial photography used in this study). This alignment is also partly apparent on the drainage network shown in Figure 11. There probably has been some movement along the underlying fault since the major part of the landslide motion occurred. The fault movement cut the overlying landslide mass, and, either through surface offset or because of structural weakening, brought about a linear zone of control on drainage development.

This control on drainage development appears to be nearly vertical, suggesting that the Verona fault is nearly vertical. That is why it is shown as a vertical fault in Figure 4. There is no geomorphic evidence for Holocene fault movement along this zone of drainage control.

This evidence for the location of the Verona fault is admittedly weak and inconclusive. The location is, however, almost exactly where Hall (1958) mapped the Verona fault (figure 2). There is geomorphic evidence for the Verona fault only between the Las Positas fault (as mapped by the writer) on the southeast, and the Pleasanton fault (as mapped by the writer) on the northwest (figure 12). There is no geomorphic evidence for the eastward and northwestward continuations of the Verona fault that Hall (1958) mapped (figure 2). The faulting to the northwest of the landslide will be discussed later, under the heading "Pleasanton fault."

D. The Las Positas Fault:

As Figure 2 shows, the writer has mapped the southwesternmost 2 to 3 kilometers of the Las Positas fault in a very different location than where Herd (1977) mapped it. There is good geomorphic evidence for the existance of 2 sub-parallel traces of the fault that extend southwestward from Arroyo Valle along almost the same trend (approximately N60E) that the fault displays in the vicinity of, and just northeast of Arroyo Valle. The annotations on Figure 12 show the evidence on which the locations of the 2 traces are based. This evidence includes vertically offset stream terraces, left lateral offset of various topographic features, benches, beheaded drainages, aligned drainages, ponded alluvium, springs, and a graben.

There is no geomorphic evidence for the existance of the southwesternmost 3 km of the Las Positas fault as mapped by Herd (1977). He mapped that part of the fault along a lithologic contact, which he apparently also assumes is a fault contact. However, there are no geomorphic features either of the type that are generated by fault offset of the ground surface or of the type that are generated by differential erosion or erosional control along a fault that has long been inactive.

The Las Positas fault, as mapped by the writer in the vicinity of Arroyo Valle and to the southwest of there, does not exhibit geomorphic features of sufficient youthfulness to indicate Holocene movement. The youngest clear evidence for fault movement is the vertical offset of 30 meter-high stream terrace surfaces on both the southwestern and northeastern sides of Arroyo Valle. The vertical offsets appear to range from 2 to 3 meters. However, an 8 meter-high terrace surface on the northeastern side of Arroyo Valle is not offset. The 30 meter-high terraces are probably at least 50,000 years old, and perhaps as much as 3 times that age. The 8 meter-high terrace surface was probably abandoned by the drainage system at least as long ago as early Holocene time.

Note, on Figure 12, that in the vicinity of Arroyo Valle the sense of offset of the terraces along the two traces of the fault indicates that the slice of ground between the traces has dropped--in the manner of a shallow graben. To the northeast of the arroyo, adjacent to the southeastern trace of the fault, the geomorphic landform is that of alluvial filling of a graben that formed on the northwest side of that trace (see annotation on figure 12).

E. THE WILLIAMS FAULT

Figure 2 shows the Williams fault as it was mapped by Hall (1958), by Earth Sciences Associates (1979), and by the writer. All 3 depictions show slightly different locations. The writer located the fault strictly on the basis of fault-generated geomorphic features (see annotations on figure 12); along this fault many of these features appear to have been generated by Holocene offset. The appearance of the geomorphic features along this fault becomes increasingly youthful and more obvious to the southeast, especially to the east of the quadrangle boundary (that area is not considered in this report). Conversely, to the northwest the geomorphic features diminish in prominence and youthfulness of appearance. It is doubtful whether the northwesternmost 2 kilometers of the fault (as mapped by the writer) has been active during Holocene time. Like the earlier workers, the writer was unable to find evidence that would allow the mapping of the fault northwestward to the Vallecitos hills. Neither the aerial photography or the available exposures on the ground show any evidence of the fault.

The topographic geometry of the trace of the Williams fault (figure 12) indicates that the fault dips to the southwest, at an angle of between 50 and 70 degrees. The geomorphic features along the fault, especially the right-deflected drainages and drainages that appear to have been beheaded by right-lateral offset, indicate that the fault has had a significant right-lateral component of offset. Within the La Costa Valley quadrangle, the fault juxtaposes high ground to the northeast against lower ground to the southwest; the Williams fault appears to be the structural boundary, on the east, of the La Costa Valley structural depression. This suggests that the fault has also had a significant component of normal offset--southwest side down--along its southwest-dipping plane.

F. THE PLEASANTON FAULT

For lack of a better name, the fault that extends to the northwest along the western side of the Vallecitos hills is herein referred to as the Pleasanton fault. It is in approximate alignment with part of the postulated Pleasanton fault that extends northwestward from the town of Pleasanton (within the Dublin quadrangle). Figure 2 shows the locations of this fault as mapped by Herd (1977) and by the writer. Herd considers the fault to be a northwestward continuation of the Verona fault, and refers to it as the Verona fault.

There is no specific geomorphic evidence for the location shown by Herd, except that it is at the immediate base of the relatively linear hill front. Trench E, located near the left margin of the quadrangle (figure 2), was excavated specifically for the purpose of establishing the existance and location of that fault. The trench, which ranged from 10 feet to 15 feet in depth, did not expose the fault.

There is geomorphic evidence for a fault near the base of the hills, but not at the base. The annotations on Figure 12 show the basis for the writer's location for the fault. The geomorphic features indicate that it is a high-angle fault that has had right-lateral offset. Note that, to the northwest, the projection of the fault is about 200 meters to the northeast of the northeastern end of trench E (figure 2).

It may appear that the base of the hills, where Herd maps the fault, is the much more probable location for the fault. However, empirical evidence is that, along strike-slip faults that juxtapose high terrane along one side of the fault against lower terrane on the other side, the trace of the fault commonly does not occur right at the base of the hill front or mountain front, but instead occurs part way up the front, typically at an elevation above the base that is equal to between 10% and 30% of the height of the front.

Although both the writer and Herd (1977, p. 14) argue that a fault must exist along this part of the margin of the Vallecitos hills, it is clear that this fault, at this time, has been very poorly defined. In other words, its location is very uncertain. However, in regard to recency of offset, it is also clear that there is no geomorphic evidence for Holocene offset, either along the trace as mapped by Herd, or as mapped by the writer.

G. Regional Tectonic Considerations:

This section of the investigation addresses the question of whether the Verona fault is a thrust fault. Because of the probable existance of the landslide, the thrust shears in the vicinity of GETR do not require a thrust fault to explain their existance. The landslide, however, does not exclude the possibility that the Verona fault is a thrust fault, or that both a landslide and thrust fault have contributed to the generation of the observed thrust features. But, local and regional tectonic characteristics do appear to exclude the existance of a thrust fault.

Looking at the regional tectonic environment in a very broad view, the depressions that are occupied by San Francisco, San Pablo, and Suisun Bays appear to have been created by a tensional tectonic setting during Pleistocene time. Looking at the area closer to the Verona fault, Sunol Valley, about 5 kilometers to the southeast of GETR, is a well defined structural graben along the Calaveras fault that clearly had much of its tectonic development during late Pleistocene time and possibly during Holocene time. The graben is caused by a component of tensional stress perpendicular to the Calaveras fault.

If the structural features cited above are in fact evidence for a northeast-southwest tensional regime in this region during the Pleistocene, then the north-south compressional stresses should have been released only by strike-slip faulting rather than by thrust faulting. However, at a very local level, it is possible that the interaction of displacements along the major faults could bring about local stresses that would result in thrust faulting. The Verona fault lies in such a tectonic setting as to make thrusting along that fault a plausible hypothesis. However, an examination of the local tectonic characteristics shows that certain very necessary evidence, needed for a thrust-fault interpretation, is absent.

The current elevation difference of more than 200 meters between Vallecitos Valley and the hills to the north represents the minimum vertical offset that must have occurred along the Verona fault. If the Verona fault is a thrust fault, and dips as steeply as 45 degrees, then the horizontal component of offset along the fault must have been at least 200 meters--in other words, it must at least equal the vertical component. If the vertical offset was significantly greater than 200 meters (assuming there has been significant erosional lowering of the hills) or the thrust fault dips at an angle of less than 45 degrees, then the horizontal component of offset would have to have been greater than 200 meters. Certainly, on the basis of the GETR investigation trench evidence, the observed thrust shears could have had that magnitude of horizontal component of offset.

If the Vallecitos hills have been thrust upward and to the south-southwest along the Verona fault, then components of that thrusting should also be evident along one or both of the adjacent faults that bound the hills--the Las Positas fault on the southeast, and the Pleasanton fault on the west. Note, on Figures 2 and 12, that the Las Positas and Pleasanton faults strike almost at right angles to one another, with the Verona fault more or less cutting off the corner. If the direction of the horizontal component of thrusting on the Verona fault were such that it almost bisected the angle between the other 2 faults (a thrust direction of about S15W), then, by geometric calculation, the component of horizontal movement perpendicular to each of the other 2 faults would be about 70% of what it is on the Verona fault. 70% of 200 meters is 140 meters. If the direction of thrusting on the Verona fault did not bisect the angle between the other 2 faults, but was more nearly parallel to one of the other 2 faults, then there would be almost no thrust component on the fault that is parallel to the direction of thrusting, but 100% of the thrusting would had to have occurred on the other of the 2 faults. Examination of the Las Positas and Pleasanton faults shows no evidence of such thrusting on either.

First consider the Las Positas fault. It is the poorest candidate for any arguements of north-over-south thrusting. 5 kilometers to the northeast of GETR, the 2 traces of that fault appear to bound a graben in between. This is especially apparent to the northeast of Arroyo Valle where, just east of the mouth of Dry Creek, a graben has formed on the northwestern side of the southeastern branch of the fault (see annotation near right margin of figure 12). The graben, of course, indicates a tensional stress regime along the Las Positas fault, not compressional as would be absolutely necessary for thrust faulting.

Therefore, if thrust faulting has occurred on the Verona fault, the horizontal component of movement would had to have been parallel to the Las Positas fault and perpendicular to the Pleasanton fault. In that case, thrust faulting, comparable in magnitude to that observed in the vicinity of GETR, should occur along the western margin of the Vallecitos hills to a point at least as far north as the site of trench E. But, to the northwest of the northwestern corner of the probable landslide boundary (as shown by the writer on figure 12), no evidence for thrusting has been found. The only attitude-specific fault evidence the writer sees in that area is geomorphic evidence for a high-angle fault.

Thus, if thrust faulting has occurred along the Verona fault, then it has occurred in an isolated manner that poses difficult problems of geometric accomodation.

Herd and Brabb (1979) argue for thrusting along the Verona fault, based on a different line of evidence. They cite evidence for left-lateral offset along the Las Positas fault, and imply that the westward movement of the northern block requires a thrust fault to the west to accommodate that movement. However, a look at the late Quaternary structural characteristics of the terrane to the south of the Las Positas fault suggests another equally plausible explanation for the accommodation of left-lateral slip along that fault.

First, consider the Sunol Valley structural graben. This graben, along the Calaveras fault, terminates abruptly on the north at a point near the southwestern end of Vallecitos Valley. This point is also nearly in line with the west-southwestward projection of the main part of the Las Positas fault. Note that the northern end of this graben is more than a kilometer wide.

The tectonic tension that caused the Sunol graben to form must have been accomplished either by the westerly movement of the block to the west of the graben, or by the easterly movement of the block to the east of the graben. To the west, there are no mapped structural features or geomorphic evidence of late Pleistocene movement that would account for the formation of the graben. But, to the east, the left-lateral Las Positas fault is an obvious candidate for accommodating the eastward movement of the block immediately east of the Sunol graben.

Consider also the geometry and sense of slip along the Williams fault (see figure 12 for its position and orientation). It is probably both right-lateral and normal. These components, together, indicate a tensional stress in an east-west direction, roughly parallel to the Las Positas fault.

The suggestion is that the left-lateral offset along the Las Positas fault may have been accommodated on the west, not by compression and thrusting on the northern side, but by extension on the southern side--as evidenced by the above-described extensional features. It should be borne in mind, however, that the two explanations are not mutually exclusive, and therefore do not resolve the question of whether the Verona fault is a thrust fault. But, Herd and Brabb (1979) make a rather cogent argument for thrusting along the Verona fault, and it is easy for the reviewer to infer that there is no other explanation for the accommodation, at the western end of the Las Positas fault, of the left-lateral movement along that fault. There is another equally plausible explanation.

VII. CONCLUSIONS

A. General:

Of all the geologic aspects of of the Verona fault, and nearby area, that are salient to the purposes of this investigation, only one is conclusive: there are north-northeast-dipping thrust shears along the northern margin of Vallecitos Valley.

These shears could have been generated by one or both of two possible mechanisms. One mechanism is large-scale landsliding, with the thrust shears representing the imbricated sole shears at the toe of the slide. The principal uncertainty about this mechanism is whether or not the postulated landslide exists. There has been a moderate amount of evidence developed both for and against the existence of the landslide, and the various investigators have made arguments both for and against its existence. Clearly, however, the evidence is not conclusive for either interpretation.

The other possible mechanism is thrust faulting, along a northwest-trending northeast-dipping fault--the Verona fault, if it in fact exists. There are two principal uncertainties about this mechanism: (1) has the Verona fault had a significant component of thrust offset, and (2) does the Verona fault, or any other fault, even exist at the northern margin of Vallecitos Valley? Again, a moderate amount of evidence has been developed to support both sides of the two uncertainties, but, also, none of it is conclusive.

An additional complication, from the point of view of this Alquist-Priolo program investigation, is that the evidence and arguments for the recency of movement on the thrust shears are also inconclusive. All of the participating investigators agree that significant movement occurred as recently as 20,000 years ago, and all agree that some movement may have occurred less than 11,000 years ago. There is not agreement that movement has definitely occurred during the last 11,000 years.

Our criteria for zoning a fault are that it must be sufficiently active and well defined. The writer cannot, based on all available evidence, make a conclusive judgement in regard to the application of either criterion to the Verona fault.

However, a zoning decision must be made, based on available evidence. If that decision cannot be made on the basis of conclusive determinations, then it must be made on the basis of the evaluation of probabilities. In the weighing of the evidence that follows, the writer is relying on a substantial amount of experience in several areas of geologic investigation. These include: (1) the use of geomorphic evidence in the detailed mapping of faults and in the assessment of their recency of surface offset, (2) the detailed mapping and classification by age of landslides, and (3) a broad empirical knowledge of the local and regional tectonic patterns associated with faults in California. This last is the result of 5 years of field-oriented fault investigations, involving both detailed and reconnaissance mapping throughout much of southern California.

B. Existence of the Verona Fault:

The writer views the existence of the Verona fault, and for that matter the existence of one or more faults along all of the southern and western margins of the Vallecitos hills, as being

very probable--at least 0.9 on a 0 to 1 probability scale. If such faults do not exist, the hill-valley topographic relationship would had to have been caused by erosional processes, which appears to be very unlikely. The trenching in the GETR area has exposed thrust shears which may be part of the Verona fault. There is also geomorphic evidence
for the existence and location for high-angle faults along the hill front, although this evidence is of relatively poor quality.

If the thrust shears that were observed in the trenches are in fact fault generated, then the Verona fault must be classified as well defined, at least in the area between trench T-2 on the northwest and Highway 84 on the southeast. If the thrust shears were generated by landsliding only, then the Verona fault is very poorly defined.

C. The Existence of a Thrust Fault:

The writer views the existence of a thrust fault along the hill front as having low probability, about 0.25. This is mainly because of the lack of any direct evidence for thrust faulting outside of the area where there is evidence for landsliding. Trench A, to the east of the postulated landslide area, revealed a fault that could reasonably be considered to be an eastward continuation of the Verona fault, but the fault at trench A is a high-angle strike-slip fault, and offers no support for the thrust fault hypothesis.

The seismicity of the area indicates a north-south, or north-northeast to south-southwest compressional stress regime. This, at face value, supplies good support for the thrust fault hypothesis. However, the geomorphic evidence along the Las Positas fault, which indicates a moderately tensional character along that fault, presents a contradiction to the seismic evidence. The tensional features along that fault are not compatible with north-south compression.

This raises a question that has not been addressed by investigators: What type of evidence is more reliable?--the geomorphic evidence that records the actual deformation that has occurred during a time span that ranges from at least 100,000 years ago up to the present, or the seismic evidence that yields direct information on the stress field that has existed in the area for the past few decades?

The only argument against the validity of the geomorphic evidence, other than that the investigator's interpretation of the geomorphic evidence may be wrong, is that if a significant long-term change in the regional stress field has occurred recently--say in Holocene time--it may not yet be reflected in the geomorphic evidence. However, such major changes in regional stress appear to occur, in any one region, only at intervals of hundreds of thousands or millions of years. So the probability of any such change having recently occurred in any given area is very low.

However, short-term changes in regional and local stress appear to be fairly common. Recent crustal strain studies, such as those conducted in connection with the Palmdale bulge, indicate that crustal strain (and therefore stress) change significantly over periods of time as short as a few years or even months (Savage and others, 1981). Also, the historical record of earthquakes in California suggests that major earthquakes on the major faults cause significant short-term changes in the regional stress--perhaps because of the rapid reduction of that stress at the time of each major earthquake, and the subsequent gradual re-accumulation of that stress.

The writer, therefore, in weighing these two types of evidence, feels compelled to place little significance on the north-south compressional thrusting argument because of the lack of geomorphic evidence for compression along the Las Positas fault.

This, however, does not rule out the possibility that the Vallecitos hills have been pushed west-southwestward, parallel to the Las Positas fault, and have been thrust northeast-over-southwest along the Verona and Pleasanton faults (or just the Verona fault by Herd's nomenclature). But, there are 2 problems with this interpretation:

(1) For the thrusts that have been observed, in the vicinity of GETR, the observed slickenside and striation directions have typically been normal to the hill front--N15E to N30E, with only some observed to trend as much as N60E. For movement to be parallel to the Las Positas fault, these should be typically N50E to N60E.

(2) The thrusts have only been actually observed within the area of the postulated landslide. Thrust faulting should continue along the hill front to the northwest--that is, to the northwest of trench T-2. No such evidence has been found, and trench E, which was excavated for the purpose of finding such evidence, did not find any.

However, trench E was not sited at the best location for its intended purpose. Note that the steep hill front, which may have been generated by an underlying thrust fault, extends northwestward only to Sycamore Road, then turns abruptly to the northeast. If thrust faulting has brought about the steep hill front, then that thrust fault is probably offset or terminated by a tear fault at Sycamore Road. Trenching at the hill front, at a point about 1 kilometer southeast of Sycamore Road, would be much more conclusive. If a thrust fault occurs along the hill front, it should not be difficult to expose it there, and there is no evidence in that area for large-scale landsliding which would pose problems of interpretation. If such trenching did not expose a thrust fault, then the trenching could be extended upslope to investigate the high-angle fault as mapped by the writer.

There is another mechanism, not considered by previous investigators, by which thrusting may have occurred along the Verona fault in the vicinity of GETR, but need not have occurred along the Pleasanton fault or any other fault in the area. If the Pleasanton and Williams fault are essentially the same right-lateral fault, with a left step of about 1 kilometer at the southern end of the Vallecitos hills, then thrusting would likely occur in the vicinity of GETR because of the right-lateral movement having to accommodate the left step.

Such compression is common at left steps in right-lateral faults in California, and the opposite effect, extension and depression, is common at right steps along such faults.

There are 3 lines of evidence, however, that appear to rule out this possible mechanism:

(1) The evidence for right-lateral offset along the Pleasanton fault is very weak.

(2) The evidence for right-lateral offset along the Williams fault weakens to the northwest, and the fault cannot be followed through to tie in with the postulated Verona thrusts.

(3) The direction of the slickensides and striations on the Verona thrusts should reflect the southeastward movement of the upper plate--that is, they should trend between N10W and N40W. Instead, they typically trend N20E to N30E.

Therefore, the writer has to rate this possible thrust fault mechanism as having a low probability.

D. The Existence of Large-Scale Landsliding:

This is a critical question, because, if the landslide does not exist, then tectonic thrusting must have occurred in the GETR area. The writer views the existence of an old large-scale landslide complex along the southwestern margin of the Vallecitos hills as having a high probability--about .75. The writer views the geomorphic evidence for the landslide as being strong, although not so strong as to be conclusive. Trenching, however, failed to confirm the existence of the landslide, and some investigators argue that the trenching confirms that a landslide does not exist. That trenching, however, had two weaknesses in regard to its usefulness for the purpose for which it was being employed:

(1) The trenches were too shallow. Those trenches were

nominally 5 feet deep, and in only a few places did they exceed a depth of 6 feet. That is insufficient for the recognition of shear planes that are not strongly developed, as would be the case for the tensional shears that develop at shallow depth in the headwall area of a landslide.

(2) Within the trenches, below the soil profile, at least two-thirds of the strata encountered (Livermore Gravels) were poorly consolidated gravels--as shown on the logs. Poorly consolidated gravels are the one geologic material that is most prone to not leaving any visible evidence of a shear plane after having been sheared. The shallow trench depth would make it extremely difficult to recognize weak shears in such materials.

Because of these weaknesses in the use of trenching as an investigative method in this case, the writer must put more weight on the geomorphic evidence for landsliding.

E. Recency of Movement Along the Thrust Shears:

The question of movement along the shears in the vicinity of GETR may be addressed even in the absence of any certainty as to the origin of the thrusting. The writer, in weighing the evidence, sets the probability of there having been 3 feet or more of Holocene offset along any of the shears at a very low value---less than .05. For smaller offset values, say from a few inches to a foot, the probability must be considered to be higher.

A substantial controversy exists among the participants of the GETR trench investigations as to whether there has been significant offset on any of the thrust shears during Holocene time. The controversy stems from differences of opinion as to what was seen in the trench walls, and over what the true ages are of the youngest faulted soil horizons. None of the evidence or arguments presented by the various investigators (as referenced and discussed earlier in this FER) are of a cogent nature--either for or against significant Holocene offset. And the writer was not present at the trench investigations, so he cannot directly assess that evidence.

However, there is one other line of evidence bearing on this question which has elicited little attention from the previous investigators. None of the exposed thrust shears are accompanied by specific surface topographic expression in the vicinity of their projections to the surface. The writer has observed obvious and well-defined scarps along thrust faults that dip as shallowly as 20 degrees, so he harbors no doubts that thrust faults are capable of generating such features. This indicates that the last significant movements along the GETR thrusts occurred so long ago that erosion has eliminated essentially all traces of the scarps that must have formed. Or, if movement is primarily by the process of creep or by many small increments of offset, then the rate of that movement is far slower than the erosional rate in that area.

This, then, begs the question: what is the erosional rate? Is it fast enough in this area for topographic features generated by significant Holocene offset to have been completely eliminated? That answer appears to be no.

In this case, the trenches provided useful evidence.

The buried dark red paleosol, which has been estimated to be more than 70,000 years old, was observed to be nearly parallel to the present ground surface in many of the trenches. This was especially true in trench E, where the paleosol was observed to be nearly paralel to the present ground surface along nearly the entire length of the trench. The northeastern third of the trench extended up a slope that is steeper than many of the slopes that are underlain by thrust shears in the vicinity of GETR, yet the parallelism was observed to be maintained, indicating a very slow rate of erosional modification of these slopes in this area.

From this evidence, the writer must conclude that the rate of erosion in the area downslope from the base of the hill front has been very slow during Holocene time, and that any offset of those surfaces of more than a foot or two would still be topographically visible. Therefore the probability of there having been more than a foot of Holocene offset along the GETR shears is low.

F. The Las Positas Fault:

This fault is moderately well defined along the northeasternmost 3 kilometers of its occurrence within the La Costa Valley quadrangle, but to the southwest of that part of the fault its definition gradually decreases. The geomorphic evidence for offset along this fault does not indicate Holocene offset except possibly along the northeasternmost one kilometer of the fault.

G. The Williams Fault:

The Williams fault, within the La Costa Valley quadrangle, is poorly defined at its northwestern end, but becomes increasingly better defined and more youthful in appearance to the southeast. The geomorphology along the southeasternmost 1 to 2 kilometers of the fault strongly suggests significant Holocene offset.

VIII. RECOMMENDATIONS FOR ZONING

Two alternative sets of recommendations are herein given for the zoning of the faults in the Vallecitos area. This is because of the lack of conclusiveness in the evidence, and the uncertainty as to how past zoning policy should be applied in this case.

The first alternative, which recommends against zoning any of the faults except the Williams fault, is based on the writer's assessment that the thrust shears observed in the trenches are more likely to have been caused by landsliding than faulting. The second alternative, which recommends extensive zoning of the thrust shears, is based on the view that the thrust shears may be part of an active thrust fault, and that it is better to err on the side of safety in this matter.

Depending on the policy decisions that are made, either alternative is consistent with the conclusions that are stated earlier in this report.

A. First Alternative:

It is recommended that the existing zone along the Verona fault (as mapped by Hall) by deleted. That fault is too poorly defined, even in the hill front area where the writer concurs with Hall on its location. Furthermore, if that is the location of the fault, there is no geomorphic evidence for Holocene offset.

It is also recommended that no zone be established along the Verona fault as mapped by Herd or by Herd and Brabb (figure 2). This recommendation is based on the failure of that postulated Verona fault to meet our zoning criteria for being sufficiently active and well defined. In this alternative, the writer interprets his assignment of a low probability for the GETR shears having been caused by faulting as representing a lack of definition of the fault. This is a situation where a precedent is needed but does not exist. In any case, the writer also assigns a low probability that the postulated Verona fault thrusts have been active during Holocene time, so it is questionable as to whether or not the "sufficiently active" criterion is satisfied.

It is recommended that no zone be established along the Pleasanton fault (as mapped by the writer), or the northwestern extension of the Verona fault (as mapped by Herd, 1977). Both faults, if either exist, are definitely not well defined, and exhibit no evidence for Holocene activity.

It is recommended that no zone be established along the Las Positas fault. Although the northeasternmost 3 to 4 kilometers of that fault within the Livermore quadrangle is fairly well defined, the geomorphic evidence does not indicate Holocene offset except possibly along the easternmost kilometer. The writer, however, would not recommend zoning there unless the rest of the fault zone extending to the northeast in the next quadrangle is also examined for the purpose of zoning.

It is recommended that a zone be established along at least the southeasternmost 3 kilometers of the Williams fault. The geomorphic evidence for offset along the southeasternmost 1 to 2 kilometers of the fault within the La Costa Valley quadrangle is nearly an order of magnitude more youthful in appearance than any such evidence that the writer has observed along the Verona, Pleasanton, or Las Positas faults. Some of the features along that part of the Williams fault are almost certainly the result of Holocene offset.

B. Second Alternative:

The recommendations for zoning along the Las Positas and Williams faults are the same for this alternative as in the first alternative. The writer also recommends that the existing zone along the Verona fault (as mapped by Hall) be deleted, for the same reasons as stated in the first alternative.

Within the La Costa Valley quadrangle, it is recommended that a zone be established to encompass all of the thrust shears observed in the GETR trenches. On the northeast, this zone should extend at least one-fourth mile upslope from the base of the hill front. To the southeast it should extend to Highway 84, and to the southwest it should extend to encompass the "landslide boundary" shown on Figure 12. The landslide boundary is chosen because it marks the limit of anomalous geomorphology in that area; if the anomalous geomorphology is not the result of landsliding, then it probably marks the southwestern boundary of the lowermost imbricate shears of the thrust fault.

Within the Livermore quadrangle, the writer recommends that a zone, at least one-fourth mile wide, be centered over the base of the hill front--esentially over the Verona fault as mapped by Herd and Brabb in that area. This zone should extend no farther to the northwest than Sycamore Avenue.

IX. INVESTIGATING GEOLOGIST'S NAME, DATE

Drew P. Smith

Drew P. Smith
Associate Geologist
March 31, 1981

I concur with recommendation B, but do not recommend zoning the Williams fault or the Las Positas fault in this study area. The Verona fault should be zoned from Hwy 84 on the east to Sycamore Rd on the NW and should include all Holocene strands, ~~(?)~~ recognizing that the thrust-fault features may be due to landsliding. The Williams fault appears to be active only where it coincides with the main headwall scarp of a large landslide. There is no substantive evidence that the Williams fault is active to the southeast in the Mendenhall Springs quad. See FER-112 re the Las Positas fault.

EWH
4/3/81

Trench number	General location of thrusts	Principal thrust		Associated thrusts		Materials displaced	Total apparent displacement, and comments
		Strike	Dip	Strike	Dip		
T-1	At base of main ridge, 3400 ft. ESE of GETR (Fault 1)	N 80 W	10 NE	EW ±	0-20 N	Livermore Gravels Older colluvium Paleo-B Stone line equivalent?	Offsets Livermore Gravels at least a few 10's of feet, perhaps as much as 100 ft. or so (based on general appearance).
T-2	Base of main ridge, 5400 ft. NW of GETR (Fault 1)	Principal thrust not identified		Many thrusts, complex, chaotic, highly variable in attitude, but mainly low angle dips. Bedding chaotically disturbed over a distance of at least 100 ft.		Livermore Gravels older colluvium Paleo-B (?)	" "
B-1	Base of main ridge, 420 ft. N of GETR (Fault 1)	N 30 W	0-15 NE (concave upward)	NW	10-35 NE (Imbrications of main thrust)	Livermore Gravels ----- Older colluvium Paleo-B --------------- Stone line equivalent--	>40 feet 8-10 feet about 2 feet
B-3	Base of main ridge, 450 ft. E of GETR (Fault 1)		15-20 NE	N 60 W	10-15 NE	Livermore Gravels ----- Older colluvium Paleo-B---------------- Stone line-------------	>28 feet 10-11 feet ~2 feet
B-2	1300 ft. SW of base of main ridge, 1050 ft. SW of GETR (Fault 2)	N 35 W	15-30 NE	N 40 W	35 NE	Livermore Gravels------ Older colluvium Paleo-B---------------- Stone line------------	>80 feet 6 feet ~3 feet
H H-1 H-2	2400 ft. SW of base of main ridge, 2400 ft. SSW of GETR (Fault 3)	N 85 W	10-25 NE	None noted		Livermore Gravels Older colluvium Paleo-B (several) (No surface soils in H) Adjacent H_1 and H_2 indicate probable displacements of stone line by a foot or so)	Offsets Livermore Gravels at least about 30 ft., perhaps much more. At least 3 paleosols present below thrust. Well expressed slicks striking N 30-40 E.

Table 1. Characteristics of thrusts exposed in the trenches. Reproduced from Table 1 of Rice and others (1979).

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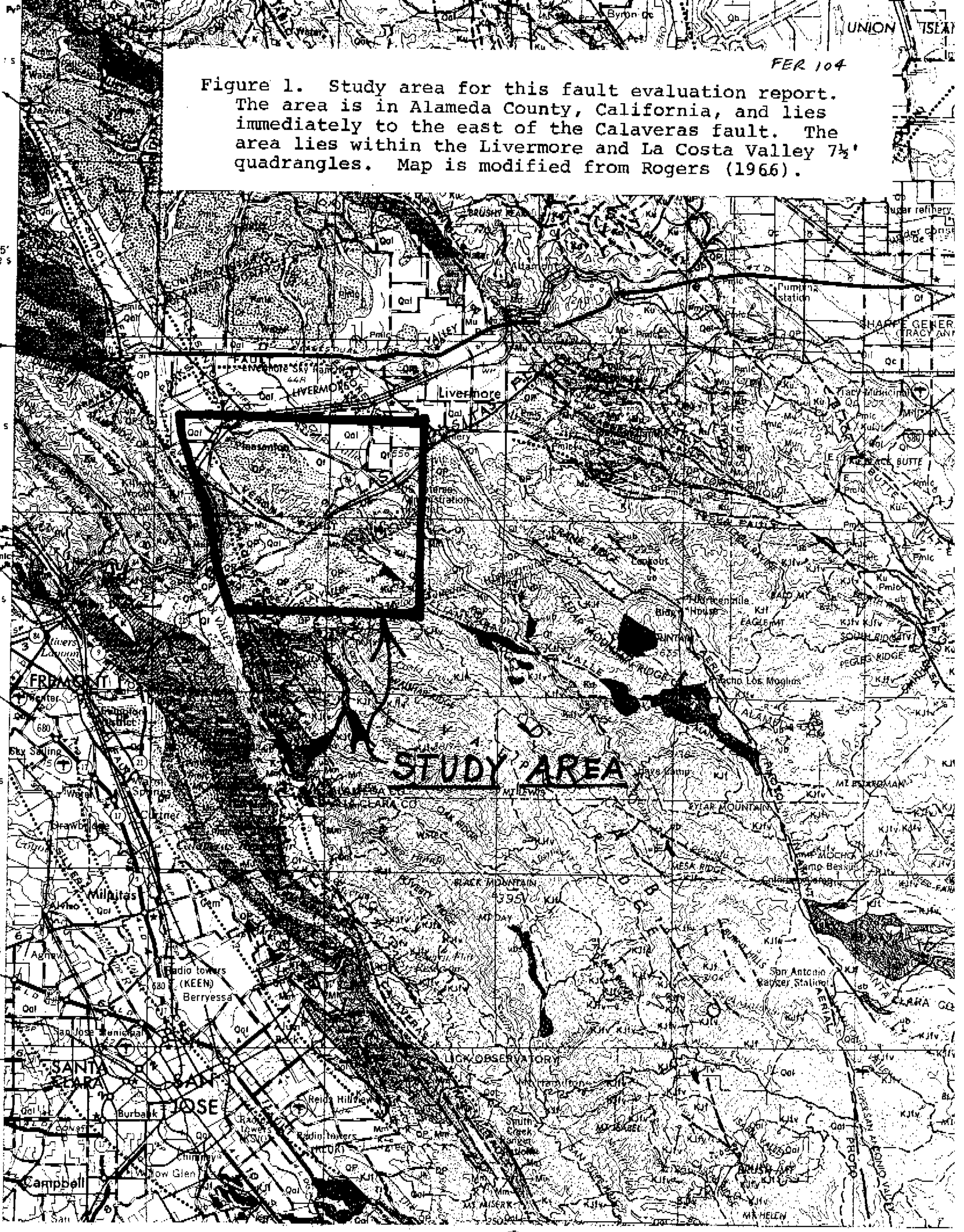
Figure 1. Study area for this fault evaluation report. The area is in Alameda County, California, and lies immediately to the east of the Calaveras fault. The area lies within the Livermore and La Costa Valley 7½' quadrangles. Map is modified from Rogers (1966).



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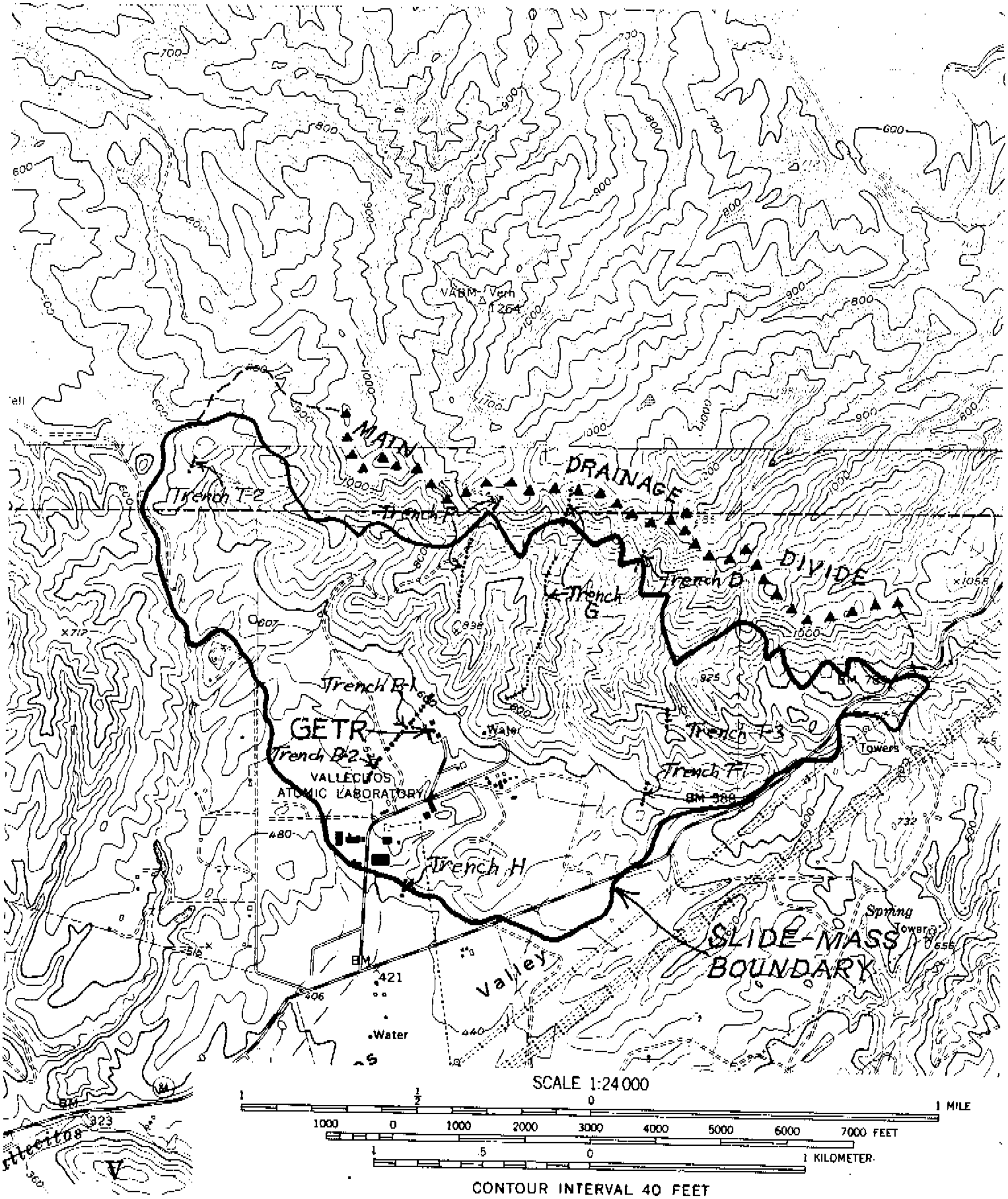


Figure 3. Location of the landslide mass, eroded head-wall area, and main drainage divide, Vallecitos area, California. Also shown are the locations of trenches B-1, B-2, D, F, G, H, T-1, T-2, and T-3.

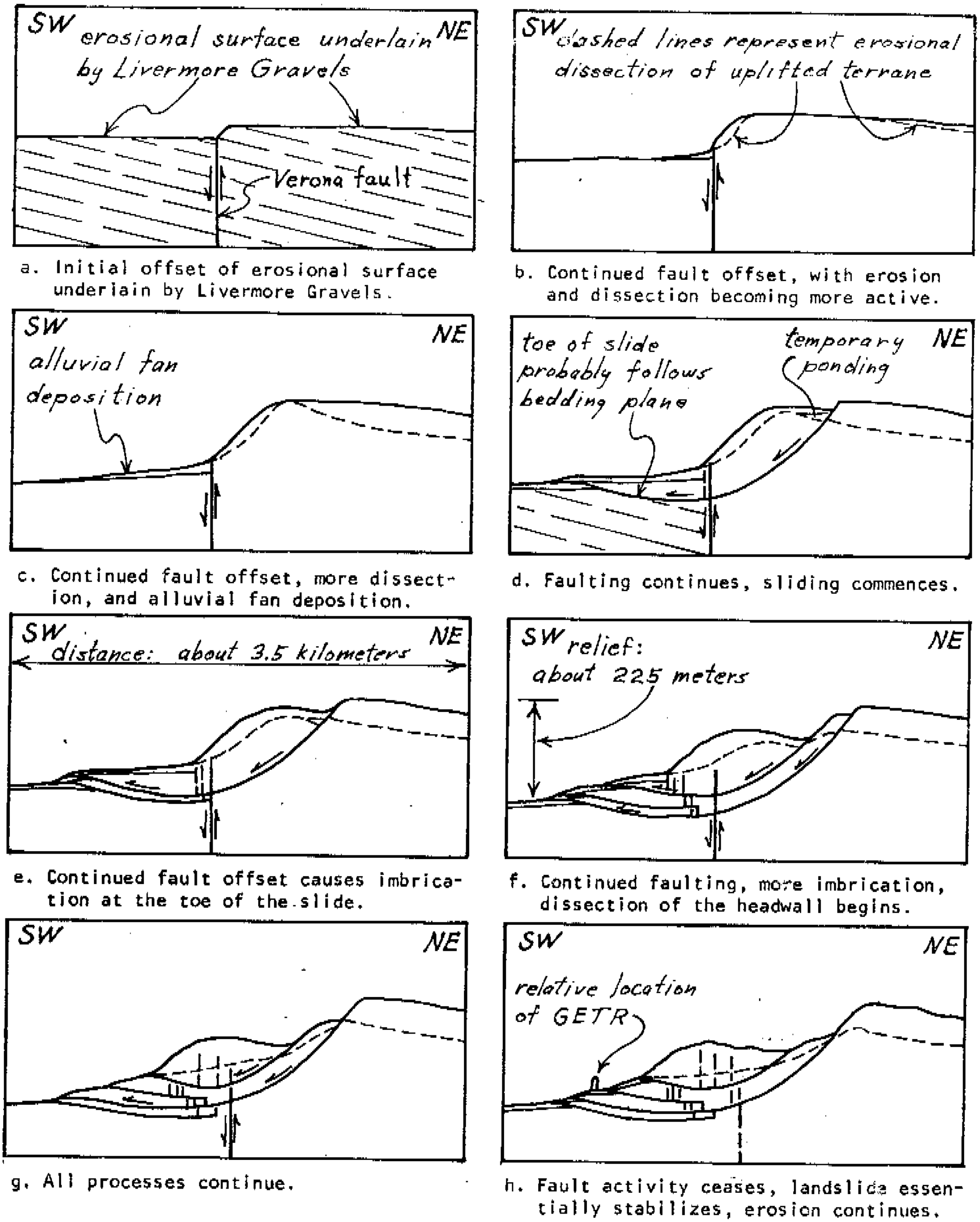


Figure 4. Postulated sequence of events in the development of the Vallecitos landslide. The sketches are diagrammatic, not to scale, and are meant to convey what happened. They are not meant to depict the exact structural configuration of the landslide.

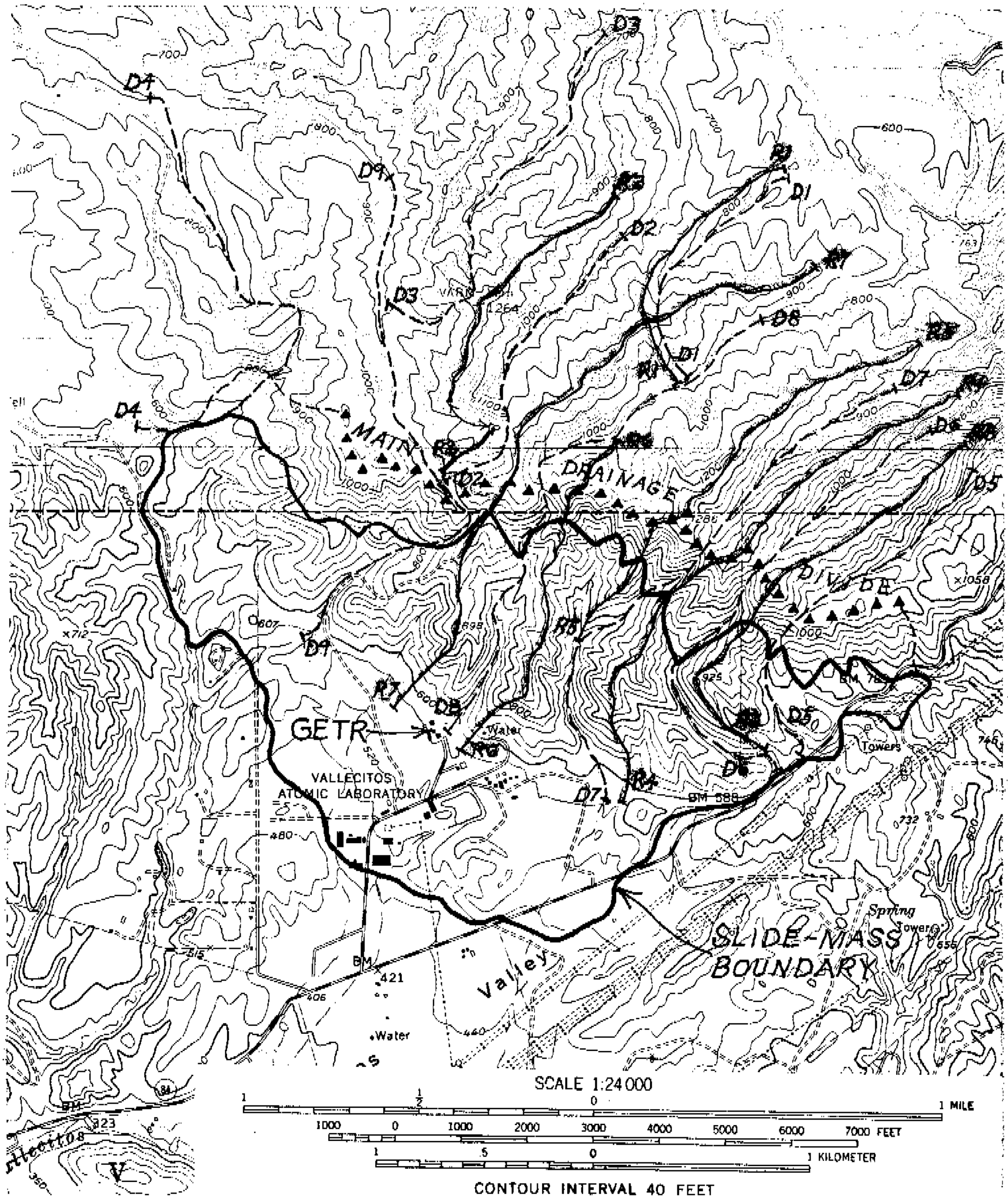


Figure 5. Location of longitudinal profiles of drainages and adjacent ridge spurs, Vallecitos area, California. Drainage profiles D1 to D4 and ridge spur profiles R1 and R2 represent "control" profiles. The other profiles extend southwestward across the main drainage divide and onto the landslide.

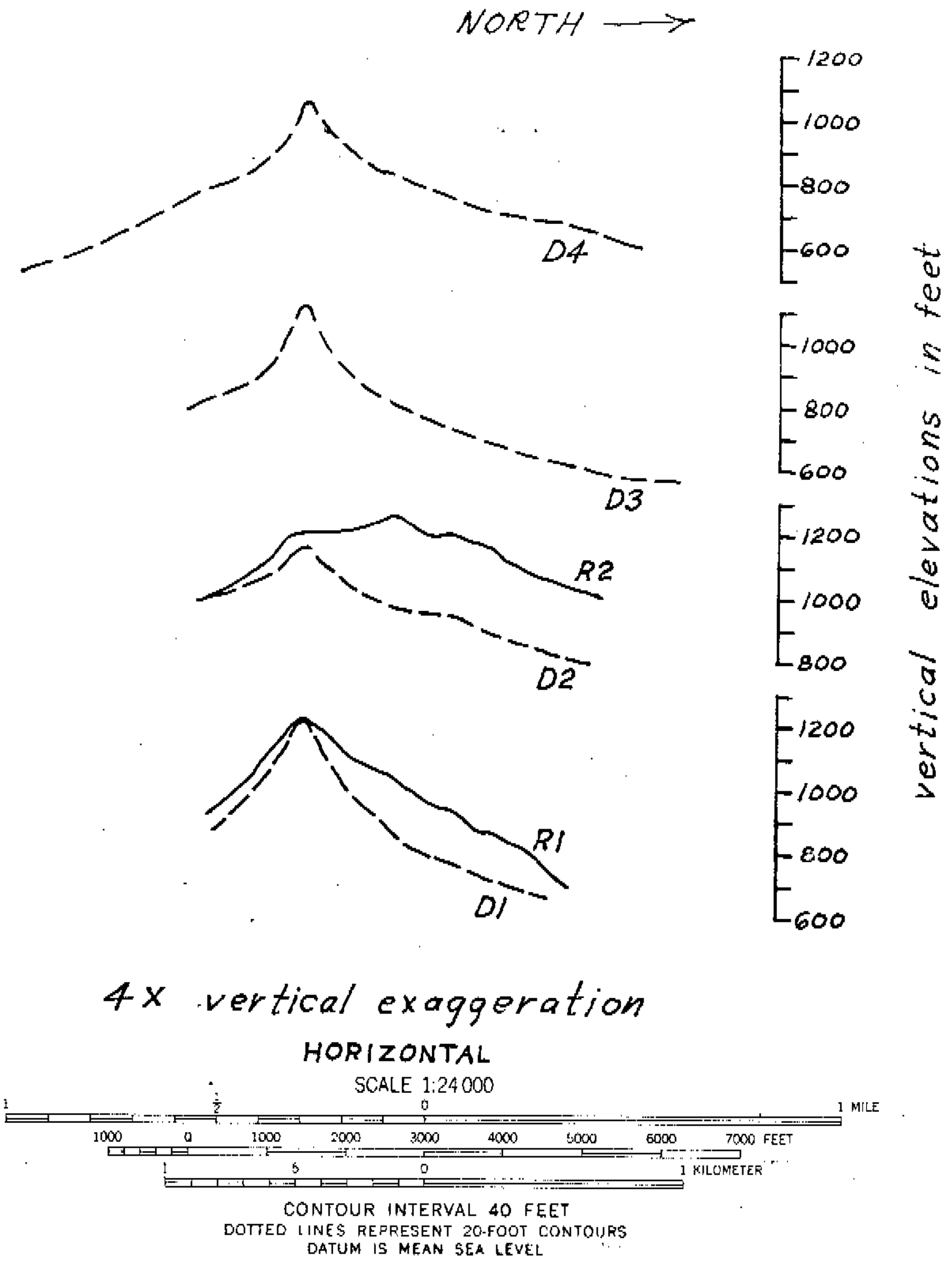


Figure 6a. Longitudinal profiles of drainages and ridge spurs to the north of the main drainage divide. These drainages have not been affected by any truncation processes. The dashed lines represent drainage profiles and the solid lines represent profiles along adjacent ridge spurs. Note the distinct increase in upward concavity in the drainage profiles near the heads of the drainages.

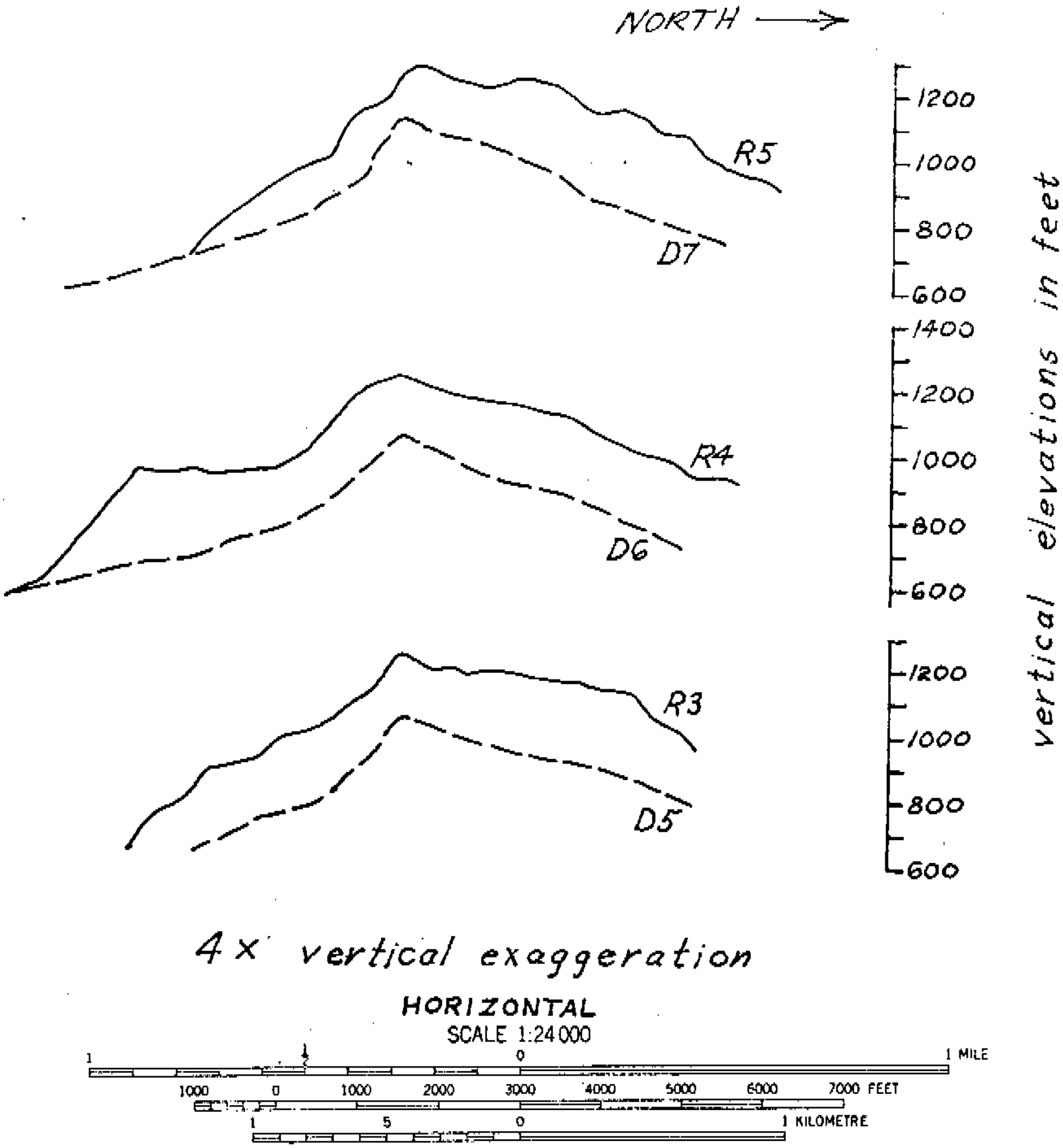


Figure 6b. Longitudinal profiles across the main drainage divide. The dashed lines represent drainage profiles and the solid lines represent profiles along adjacent ridge spurs. Note the lack of increased upward concavity near the heads of the northeastward-flowing drainages.

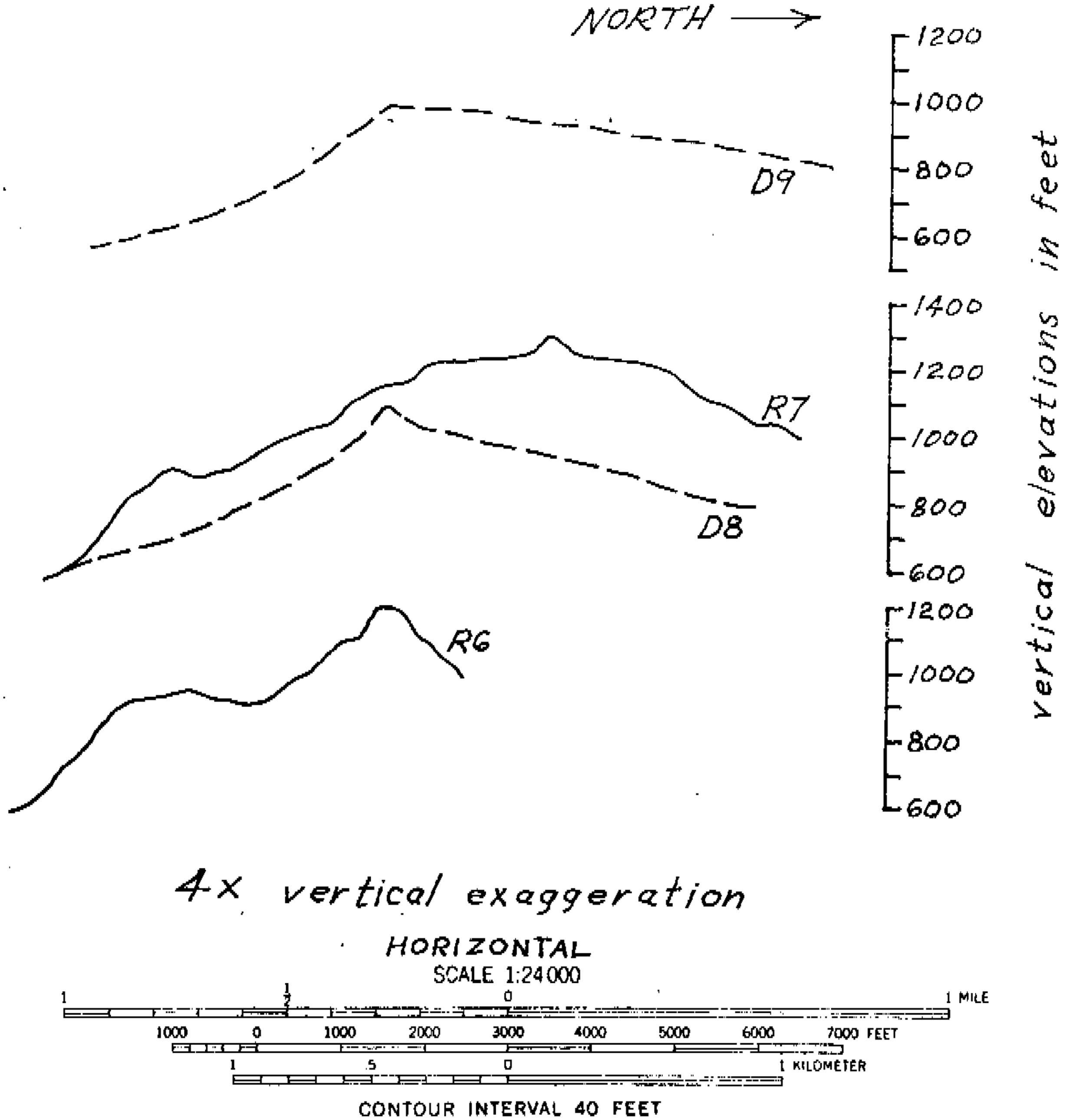


Figure 6c. Longitudinal profiles across the main drainage divide. The dashed lines represent drainage profiles and the solid lines represent profiles along adjacent ridge spurs. Note the lack of increased upward concavity near the heads of the northeastward-flowing drainages.

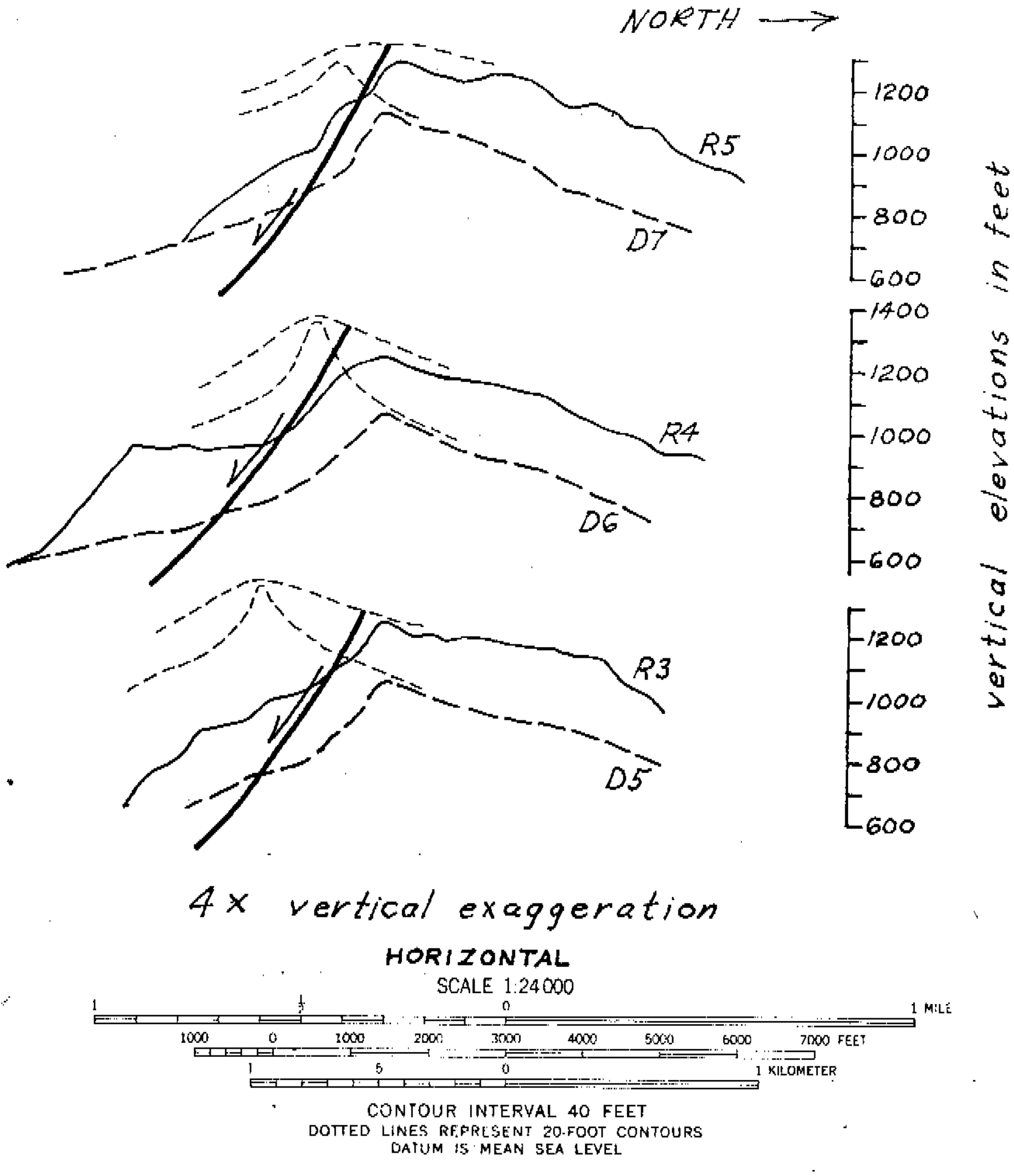


Figure 7a. This is the same as Figure 6b except that some of the profiles from the control drainages shown in Figure 6a have been superimposed (short dashed lines) on these profiles. A "best fit" match of the profile gradients was employed to show approximately how much of the original heads of drainages D5 through D7 has been truncated. Possible locations of landslide slip planes are also shown.

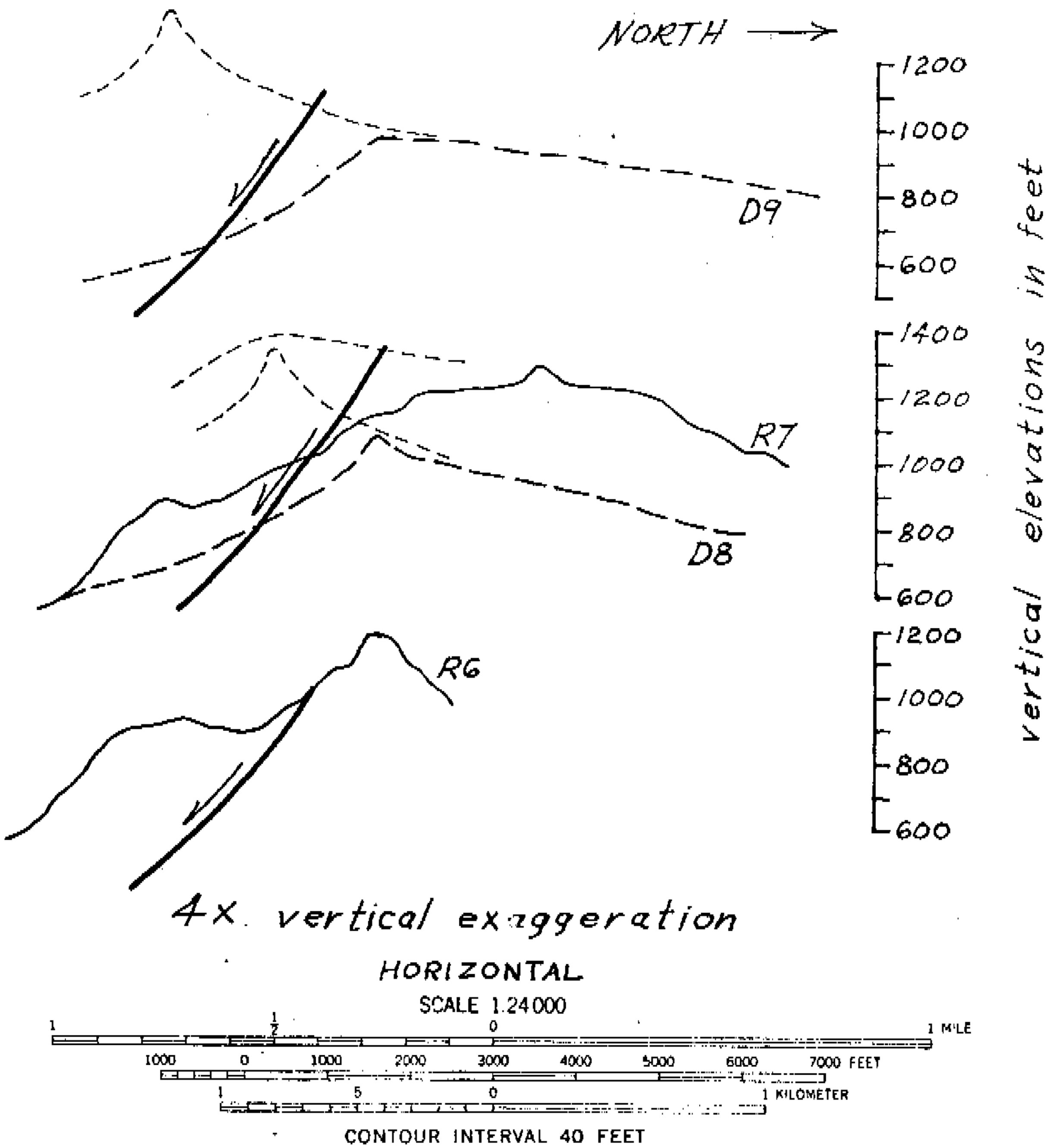


Figure 7b. This is the same as Figure 6c except that some of the profiles from the control drainages shown in Figure 6a have been superimposed (short dashed lines) on these profiles. A "best fit" match of the profile gradients was employed to show approximately how much of the original heads of drainages D8 and D9 was truncated. **Possible locations of landslide slip planes are also shown.**

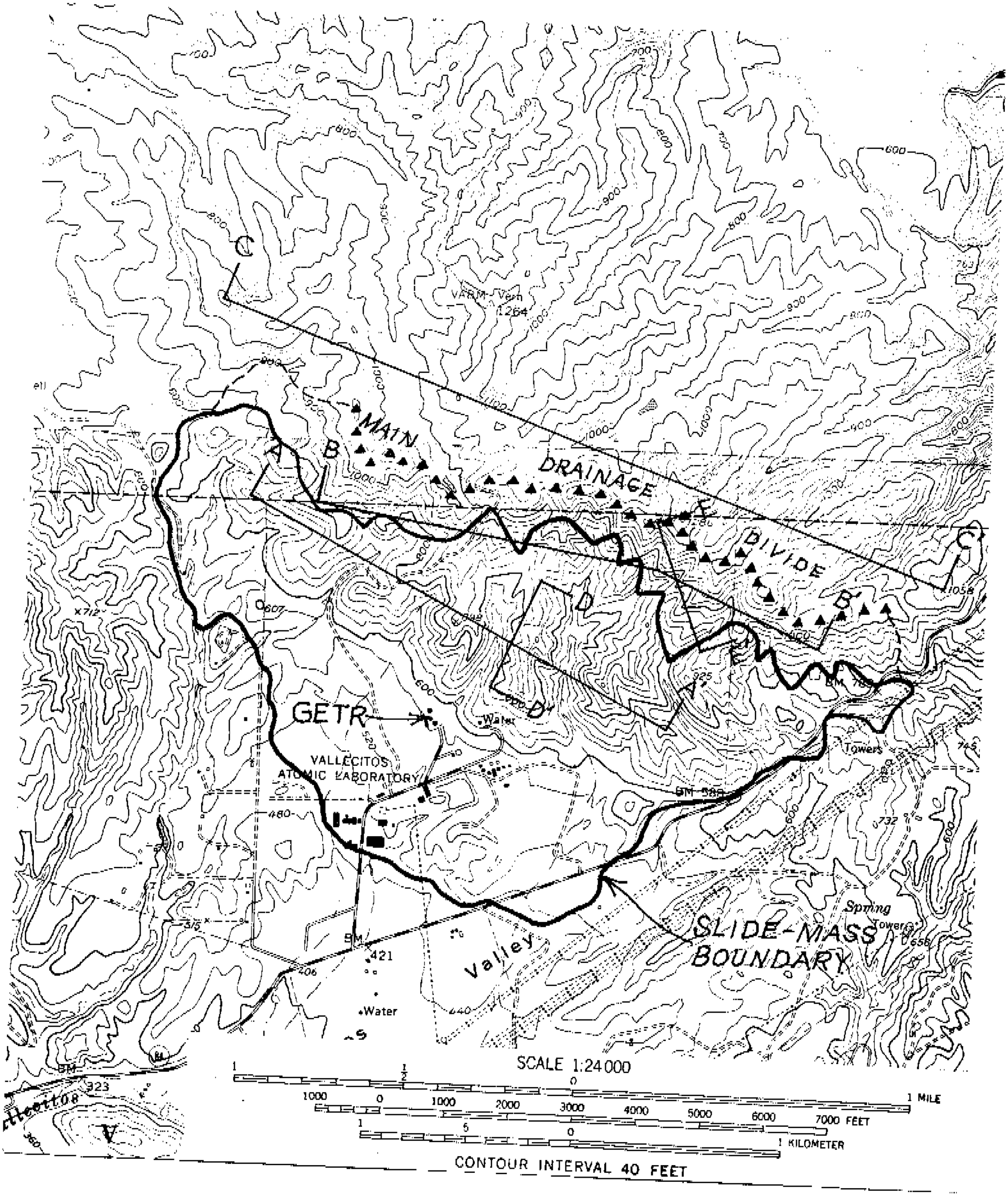
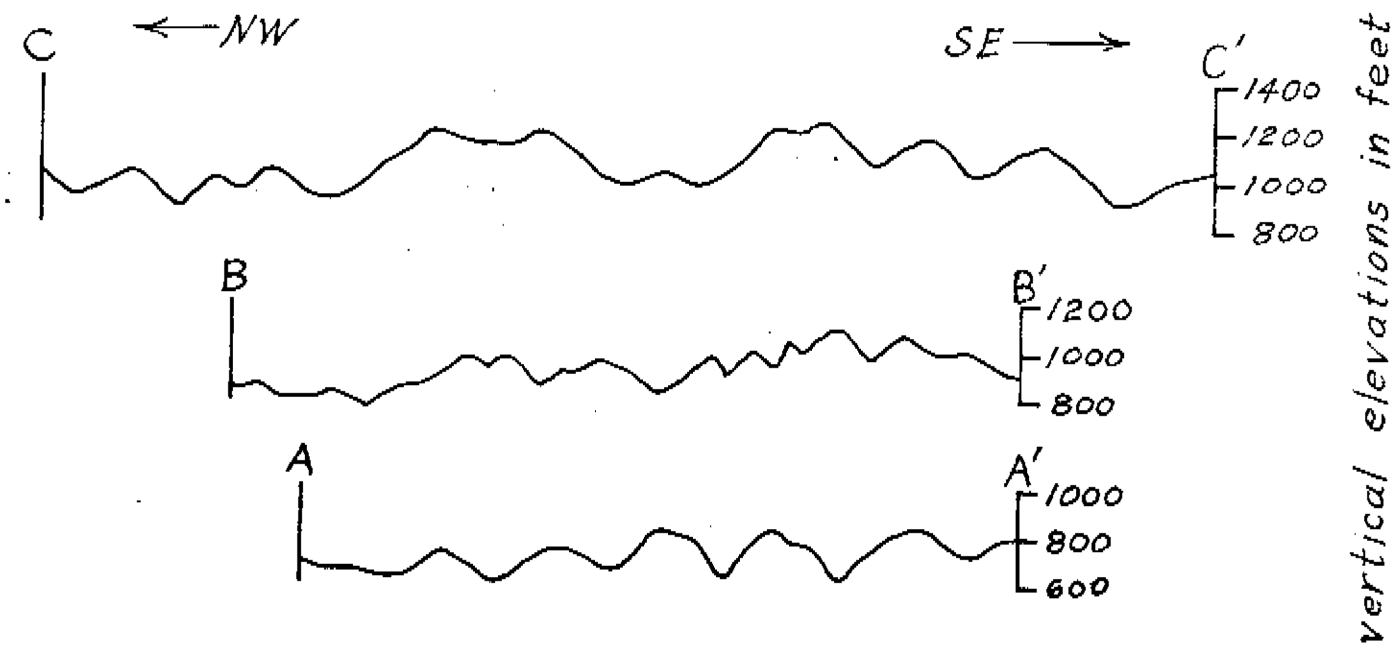


Figure 8. Locations of topographic cross sections AA' through EE'.



2.5 X VERTICAL EXAGGERATION

HORIZONTAL SCALE:

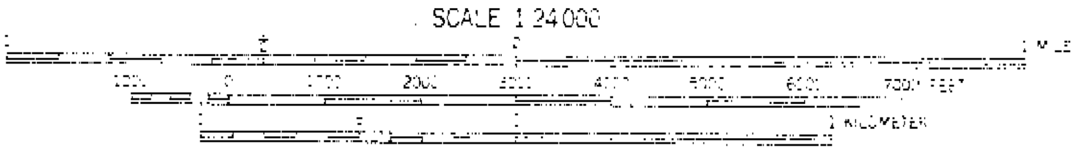
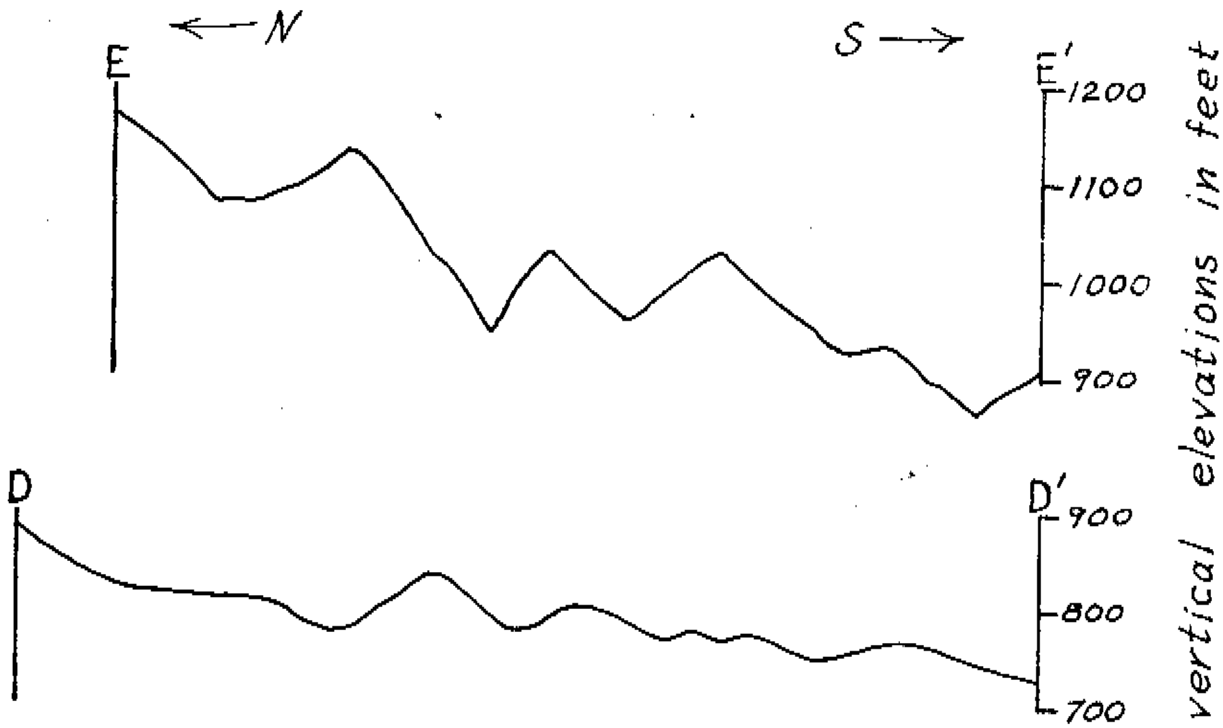


Figure 9. Topographic cross sections AA', BB', and CC'. Figure 8 shows the locations of these sections. Note the substantially lower relief and pitch of the ridge and valley topography in section BB', suggesting less mature dissection in that area.



2 X VERTICAL EXAGGERATION

HORIZONTAL SCALE:

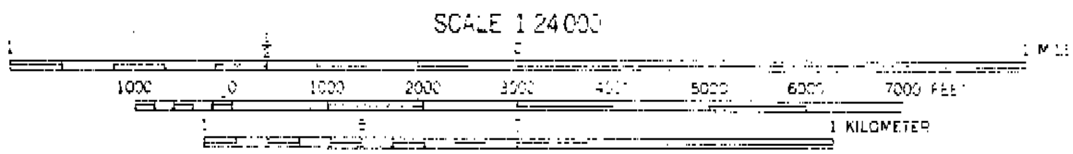


Figure 10. Topographic cross sections DD' and EE'. Figure 8 shows the locations of these sections. Both sections are across drainages that have dissected slopes of approximately equal steepness. Note the "sawtooth" cross sectional shape of the drainages at section EE', as compared to the more "sine wave" shape in section DD'. EE' is taken across the eroded headwall area, and is characteristic of erosion on slopes having little soil development. With more maturity, and soil development, the "sine wave" cross sectional shape shown in section DD' is more characteristic.

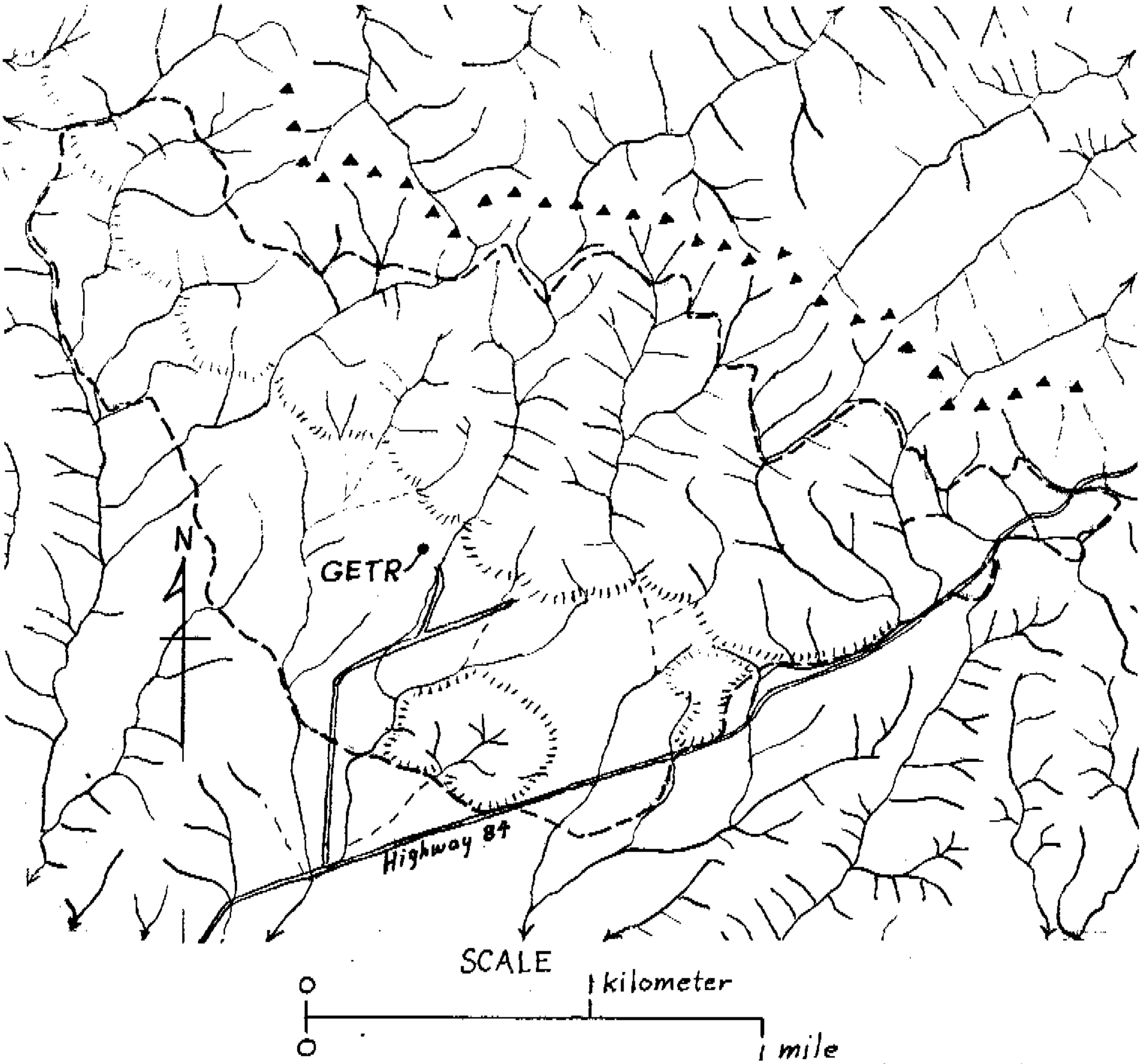


Figure 11. Areal distribution of drainages in the Vallecitos area. The triangles show the location of the main drainage divide, and the dashed line shows the approximate boundary of the landslide mass. Note that all drainages in the headwall area (between the main drainage divide and the landslide boundary) consistently flow to the southwest, with none of the branching or perpendicular tributaries that characterize the rest of the region.